COMPARING CITY-SCALE GREENHOUSE GAS (GHG) EMISSION ACCOUNTING METHODS: IMPLEMENTATION, APPROXIMATIONS, AND POLICY RELEVANCE

by

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ABSTRACT

More than 1,200 cities worldwide are embarking on low carbon goals. However, currently there are no protocols in place to consistently account for GHG emissions associated with cities. Thus, this thesis explores mathematical relationships, approximations, implementation challenges, and policy relevance for three city-scale GHG emission accounting methods: Purely Territorial, Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF), and Consumption-Based Footprint (CBF).

Mathematical relationships using Single-Region Input-Output, and Multi-Region Input-Output models showed that neither TBIF nor CBF provided a more holistic accounting of trans-boundary GHG. A typology of cities defined as: *net-producers*, *net-consumers*, and *trade-balanced* in terms of their GHGs embodied in trade is important for understanding the trans-boundary supply-chains serving cities. Data inputs for TBIF are found to be more robust and readily available, compared to CBF.

A meta-analysis of 21 US cities showed that trans-boundary electricity generation, air travel, fuel refining, along with the production of food, cement, and iron & steel, may be well-suited for allocation to cities based on their use in city-wide residential-commercial-industrial activities in the TBIF method.

Territorial GHGs captured as little as 37% of the total (in-boundary plus trans-boundary) footprint for net-consumer cities, and as large as 68% for net-producers. On average, TBIF captured 75% (n=2) of the total footprint for net-producers, 63% (n=11) for trade-balanced, and 62% (n=8) for net-consumer cities. In contrast, CBF captured an average of 35% (n=2), 57% (n=11), and 71% (n=8) of the total footprint for net-producers, trade-balanced, and net-consumer cities, respectively.

Various metrics of GHG emissions computed for the three methods were assessed for their ability to appropriately compare cities'. For territorial GHG, neither

$GHG^{Territorial}$/capita nor $GHG^{Territorial}$/GDP reflected urban efficiency of cities. For TBIF, GHG^{TBIF}/GDP with only electricity allocated (R^2=0.62), and GHG^{TBIF}/GDP with the additional suitable infrastructures allocated (R^2=0.77), correlated well with an urban efficiency index (UEI) composed of commercial-industrial production efficiency, household energy efficiency, and transportation system efficiency. However, GHG^{TBIF}/capita showed poor correlation (R^2=0.1) with the UEI as expected from a production-based account. In contrast, for CBF, GHG^{CBF}/capita and GHG^{CBF}/GDP showed an improved correlation (R^2=0.4) with the UEI. However, GHG^{CBF}/capita correlated more strongly (R^2=0.76) with per capita expenditures. These data suggest that GHG^{TBIF}/GDP is the appropriate metric for comparing cities based on their urban efficiency, and that GHG^{CBF}/capita is appropriate for viewing cities from a consumption perspective. For the 21 cities modeled, GHG^{TBIF}/GDP ranged from 154 mt-CO_2e/GDP to 747 mt-CO_2e/GDP, and GHG^{CBF}/capita ranged from 15 mt-CO_2e/cap to 32 mt-CO_2e/capita.

The TBIF was implemented in Delhi, India to explore issues of data availability and transferability of methods from the US to rapidly industrializing nations. Fieldwork showed sufficient availability and adaptability of TBIF methodology from the US to India yielding GHG^{TBIF} equal to 948 mt-CO_2e/GDP in Delhi vs. 413 mt-CO_2e/GDP in Denver. Broad energy use metrics between Delhi and Denver help explain differences between the two cities. All GDP in this thesis represent 2008 real USD.

Given that TBIF captured the majority of the total GHG footprint (62%–75%) in 21 cities in the meta-analysis, was well correlated with the urban efficiency performance of cities, and could be readily implemented in the US and internationally, this thesis finds TBIF to be well suited for international GHG protocols that aim to compare city-efficiencies.

The form and content of this abstract are approved. I recommend its publication.

Approved: Dr. Anu Ramaswami

DEDICATION

To everyone with a desire to achieve. The future is in your hands.

"One of the greatest things you have in life is that no one has the authority to tell you what you want to be. You're the one who'll decide what you want to be. Respect yourself and respect the integrity of others as well." – Jaime Alfonzo Escalante Gutierrez

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1. Introduction

The United Nations (UN) reported the world's population in 2007 at 6.4 billion people, and projects 8 billion people by 2025, and 9.2 billion by 2050. Also in 2007, for the first time in human history, more than half of the world's population was living in urban areas (UN, 2007). According to the UN, between 2007 and 2050, the world's urban population will increase from 3.3 billion people, to 6.4 billion people. By 2025, 57% of the world's population will be located in urban areas, and by 2050, 70% of the world will be living in urban areas; suggesting most of the forecasted population growth will occur in urban areas. Although the definitions of urban/metropolitan take various meanings around the world (UN, 2008), the definitions as acknowledged by the US Census are presented in Table 1-1.

Table 1-1: U.S. Census definitions of urban, metropolitan, and rural (Census, 2007).

Type	Population Criterion	Density (people/square mile)
Urban Area	≥ 50,000	≥ 1,000
Metropolitan Area	≥ 100,000	≥ 1,000
Rural	All those not classified as Urban	

Urban areas in the United States (US) house 80% of the total national population of 300 million people (Census, 2007). This growing urban population is forecasted to reach 86% by 2025, and 90% in 2050 (UN, 2007). The US' South and West regions have had the highest rates of population growth, roughly 1.5 times the national average (Census, 2010). The high urban population growth is expected to place much stress and create great challenges in terms of infrastructure provisioning in the context of limited natural resources. Primary energy, water, food, and land, are some of the resources that urban dwellers will be competing for.

Cities are also significant contributors to the global Greenhouse Gas (GHG) emissions. For example, it has been estimated that 70% of GHG emissions globally are attributed to energy use in cities (IEA, 2008b). Because cities are major contributors to GHG emissions, cities can also be important in GHG emission mitigation (Alberti & Susskind, 1996; N. Grimm et al., 2008). Treaties, such as the Kyoto protocol (ICLEI, 2009) and the US mayor's climate protection agreement (Mayors, 2010), must establish rigorous baseline GHG emission inventories that provide holistic GHG accounting at the city-scale, and support regionally measurable GHG mitigation. However, there are three core issues confounding city-scale GHG emission accounting:

> 1) The smaller spatial scale of cities causes artificial truncation of human activities such as commuter travel at the geographic boundary.
>
> 2) Essential infrastructures serving urban needs such as electricity power plants, airports, petroleum refineries, etc., cross city boundaries, hence termed trans-boundary infrastructures.
>
> 3) Beyond infrastructures, there are significant exchanges (i.e. trade) of goods and services across city boundaries.

Thus, GHG emissions associated with cities can broadly be classified as in-boundary or trans-boundary GHG emissions.

The idea of scopes is one way of separating in-boundary & trans-boundary, as was introduced by the World Resources Institute (WRI) GHG protocol for corporate GHG emissions (WRI, 2004). Scopes help define organizational boundaries for GHG emissions. The three scopes, and their definitions are:

> **Scope 1:** in-boundary, direct GHG emissions resulting from natural gas combustion, and tailpipe emissions from vehicle fuel combustion.
>
> **Scope 2:** indirect GHG emissions from purchased electricity used in the community.
>
> **Scope 3:** all other indirect GHG emissions linked to activities within the city.

While Scopes 1 and 2 are required reporting, EPA & WRI recommend a small number of Scope 3 items to create win-win supply chain GHG mitigation strategies (EPA, 2007). But as will be shown in Chapter 2, there is considerable variability on how to allocate in-boundary & trans-boundary GHG emissions to cities in the form of GHG inventories & footprints.

At the national scale a significant amount of in-boundary GHG emissions from commercial-industrial activities are consumed within the country's boundary (e.g., the U.S.). On the other hand, cities have unique specializations, which lead to unique trans-boundary flows. For instance, ski resort communities have disproportionately higher commercial energy use resulting from the export of services. Suburban communities have higher residential energy use, minimal commercial-industrial energy use, and higher imports of consumer goods and services. Larger metro cities provide both jobs and residence for many, and may be balanced (combination of producers & consumers). The challenge then, is in developing a consistent GHG accounting framework for diverse city types.

The overall goal of this dissertation is to compare the three leading city-scale GHG emission accounting methods side-by-side, evaluating implementation of methods, testing mathematical relationships that may allow for approximations, and identifying suitable metrics for increased policy relevance. This thesis is organized into four (4) additional chapters, and conclusion.

Chapter 2: Literature review and overview of city-scale GHG emission accounting methods.

Chapter 3: Determine mathematical relationships between the methods to facilitate approximations (simplifications), when appropriate, based on city typology.

Chapter 4: Meta-analysis of 21 US cities to explore the nature and size of their trans-boundary supply-chains, and explore the relevance to metrics.

Chapter 5: Address translation of geographic-based methods to rapidly industrializing countries, with specific attention to data availability in India.

Chapter 6: Conclusions, Contributions and Future Work.

2. Literature Review of City-Scale GHG Emissions Accounting Methods

Cities are home to a large proportion of the world's people, as a result they are being recognized as major contributors to global greenhouse gas (GHG) emissions. There is a need to establish baseline GHG emission accounting protocols that provide consistent, reproducible, comparable, and holistic GHG accounts that incorporate in-boundary and trans-boundary GHG impacts of urban activities and support policy intervention. This chapter provides a synthesis of previously published GHG accounts for cities by organizing them according to their in-boundary and trans-boundary inclusions, and reviewing three broad approaches that are emerging for city-scale GHG emissions accounting: Geographic accounting, Trans-Boundary Infrastructure Footprint (TBIF), and Consumption-Based Footprint (CBF). The TBIF and CBF footprints are two different approaches that result in different estimates of a community's GHG emissions, and inform policies differently, as illustrated with a case study of Denver, CO. The conceptual discussions around TBIF and CBF indicate that one single metric (e.g., GHG/person) will likely not be suitable to represent GHG emissions associated with cities, and it will take a combination of variables for defining a low-carbon city.

2.1 Introduction

In 2007, for the first time in human history, more than half of the world's population was living in urban settings (UN, 2007). According to the UN, the world's urban population is projected to increase from 3.3 billion people in 2007, to 6.4 billion people in 2050. By 2025, 57% of the world's population will be located in urban settings, and by 2050, 70% of the world will be living in urban settings. The US is also witnessing large rates of growth in urban population, particularly in western states such as Colorado and Arizona. US metropolitan areas are home to 80% of the total national population of 300 million people (Census, 2007). The percentage of the US urban population is forecasted to reach 86% by 2025, and 90% in 2050 (UN, 2007).

Cities are home to a large proportion of the world's people, and as a result are being recognized as major contributors to the global Greenhouse Gas (GHG) emissions (N. Grimm, et al., 2008; IEA, 2008b), as well as a critical part of the solution, addressing both GHG mitigation and climate risk adaptation (Alberti & Susskind, 1996). Cities worldwide have signed onto the Kyoto protocol, pledging to reduce greenhouse gases (GHG) by 7% by 2012 from 1990 baseline levels (ICLEI, 2009). More recently, Mexico City mayor Marcelo Ebrard and ICLEI, convened 138 cities and signed the Global Cities Covenant on Climate – otherwise known as the Mexico City Pact. The pact promises to have cities report on their respective GHG emissions and climate mitigation activities (WMSC, 2010). In the US, one thousand forty four mayors' have also committed their communities into some type of GHG mitigation (Mayors, 2010). However, such treaties must establish baseline GHG emission inventories that provide consistent, reproducible, comparable, and holistic (in-boundary and trans-boundary) GHG emission accounts with support for policy intervention.

There are three primary challenges in holistic GHG accounting at the city-scale that considers the full impact of urban activities on global GHG emissions. The three challenges are (Hillman & Ramaswami, 2010; G. P. Peters, 2010; Ramaswami, Hillman, Janson, Reiner, & Thomas, 2008):

1) Due to the relatively small spatial scale of cities, important human activities such as commuter travel and air travel, etc., are artificially truncated at the city's geographic boundary,

2) Cities are also served by trans-boundary infrastructures such as electric power plants, oil refineries and pipelines, etc., that extend beyond city boundaries;

3) Last, beyond infrastructures, there are significant exchanges (i.e. trade) of goods and services across boundaries.

Because of the above three trans-boundary phenomena, it is being increasingly recognized that human activities in cities can stimulate emissions within their geographic boundary, as well as those outside, i.e., trans-boundary GHG emissions. Thus, measuring only energy use and GHG emission strictly within a city's boundary can provide an incorrect and even misleading picture. In some cases establishing a purely geographic measurement approach may create unintended incentives to simply move GHG emissions outside the boundary. As society considers new technologies, design strategies and policies for low-carbon cities, it is imperative that we have clearly defined methods for holistic measurement of GHG emissions associated with cities, addressing both in-boundary and trans-boundary emissions.

In the past, the complexity of dealing with in-boundary and trans-boundary emissions has led to various inconsistent ways of GHG accounting at the city-scale. The objective of this chapter is twofold:

- To provide an overview of past literature on GHG accounting, listing the in-boundary and trans-boundary inclusions.
- To highlight two leading theoretical and emerging approaches for GHG emissions footprinting at the city scale, incorporating trans-boundary inclusions.

Where other works discuss GHG footprinting methods in a general sense, the value added of this chapter is in the exemplification of GHG footprinting methods and results through actual data from a Denver, Colorado case study. We conclude by briefly discussing how ICLEI-USA is incorporating these leading approaches into the community-scale GHG emissions accounting and reporting protocol (ICLEI, 2011), which is a framework being developed to help standardize GHG emissions accounting in US cities.

2.2 Review of City-Scale Community-Wide GHG Emissions Measurement

The lack of standardized methods for city-scale GHG emissions accounting to-date has produced inconsistent accounting approaches for cities throughout the world. This inconsistency is seen both in the wide variation of inclusions in city-scale GHG emissions accounting in the peer-reviewed literature, and lack of explicit statements on what the unit of analysis is – i.e., who is the accounting being done for? Is the unit of analysis, household consumption, community-wide energy use, etc.?

A first lack of clarity (or confusion) arises between GHG measurements produced for city municipal governments and those that attempt to measure cities as a whole, i.e., whole communities that comprise a city. This issue is easily dealt with by referring to the city-government emissions as *Local Government Operations* (ICLEI, 2010) while the citywide analysis can be referred to as *Community-Wide GHG accounting*. This chapter (and thesis) is solely concerned with community-wide GHG accounting for cities; however, we mention this distinction to develop a consistent vocabulary in the literature going forward. Moreover, even the term community-wide GHG accounting does not clearly address who the GHG accounting is being done for, i.e., what is the unit of analysis? Sometimes it is done for the "entire community" encompassed within a city's geopolitical boundary, i.e., residences, businesses and industries located within the geopolitical boundary, termed the geographical-based approach in our review. At other times, GHG accounting appears to address primarily the consumption by households within a community – a subset of a full consumption-based footprint approach although many researchers are not explicit in such delineation in their papers. Lastly, when GHG accounting addresses economic final consumption (i.e., *households*, *government*, and *capital expenditures* within a community), this is termed full consumption-based accounting.

So, what is a GHG footprint? Broadly speaking a "footprint" describes GHG emission of an activity beyond the boundary of the organization or entity for which the footprint is being computed (Hillman & Ramaswami, 2010; G. P. Peters, 2010; Wright, Kemp, & Williams, 2011). Thus GHG emission footprints associated with cities seeks to measure and allocate the in-boundary and trans-boundary GHG emissions associated with cities in a manner that provides rigorous data and informs policy-making. One-way of describing in-boundary & trans-boundary GHG emissions, is through the idea of scopes, developed by the World Resources Institute (WRI) for corporate GHG emissions reporting (WRI, 2004). The concept of scopes helps define organizational boundaries for GHG emissions, and can be mapped to activities associated with cities as shown below:

> **Scope 1** – GHG emissions include all direct GHG emissions resulting from in-boundary fossil fuel combustion (natural gas, fuel oil, gasoline, diesel, etc.), non-energy industrial processes, and waste.
>
> **Scope 2** – indirect GHG emissions from imported electricity used within the community boundary.
>
> **Scope 3** – all other indirect GHG emissions linked to supply chain lifecycle of materials and energy carriers used within the boundary that are produced outside. Note, in a consumption-based approach, one must also subtract the lifecycle GHG emissions from products that are produced within the boundary that are exported for consumption elsewhere, and can be shown as a Scope 3 subtraction.

Apart from helping define organizational boundaries, the concept of scopes also provides the means for preventing double counting of GHG emissions. For example, a city generating some of its total electricity use through a power plant located within its boundary would count those GHGs as Scope 1. Meanwhile, power plant GHG from generating any additional imported electricity (not locally generated) used in the city would be counted as Scope 2, as these GHG are physically occurring outside of the city boundary. Moreover, a city's GHGs resulting from the generation of surplus electricity (i.e., exports) should be allocated out based on demand to avoid double counting both at the source and point of use. In other words, the surplus electricity generated locally for use elsewhere should be subtracted from the Scope 1 of the generating city, and reported as Scope 2 for the using city. If allocation of Scopes 1 and 2 are done correctly for all cities and regions in a country, their sum should total that country's territorial (Scope 1) GHGs.

Similar issues arise when accounting for indirect GHG from other infrastructures (Scope 3). Scope 3 GHG may be added directly to a city's Scope 1+2 GHG, avoiding double counting with the community's GHG that may double count another community's Scope 1+2 GHG. This is why indirect supply-chain GHGs from infrastructures are shown as

Scope 3. In summary, inclusion of indirect GHG emissions (Scopes 2 and 3) warrants careful allocation of GHG to avoid double counting (Ramaswami, et al., 2008). Infrastructures such as large electric power plants, or oil refineries are easily recognized within city boundaries, and their GHG can be readily allocated based on local demand, thus reducing the potential for double counting.

Scopes 1 and 2 are required reporting for corporate accounting, though EPA & WRI recommend a small number of Scope 3 items to create win-win supply-chain GHG mitigation strategies (EPA, 2007). However, cities are not like corporations, and there is considerable variation on how to allocate in-boundary & trans-boundary GHG emissions to cities. Table 2-1 shows peer-reviewed studies that have accounted for various subsets of in-boundary (Scopes 1+2) and trans-boundary (Scope 3) GHG emissions relating to activities within cities. Note, although we follow typical nomenclature by showing Scope 2 as in-boundary, most electricity used in cities is generated outside, thus potentially allowing to be classified as trans-boundary.

Brown et al. (2009) inventoried GHG emissions for 100 US cities, and in their method, accounted for emissions resulting from in-boundary residential electricity use and fossil fuel (cooking and heating) use, and fuel combustion in road transport & freight within each city. Neither commercial nor industrial activities within the boundary were included due to "complex processing issues", as stated by the authors. Parshall et al. (2010) also considered multiple US cities, and sought to evaluate the GHG Vulcan data product and its ability to measure fossil fuel energy use in combustion in US urban areas. Due to Vulcan's focus on point of combustion, emissions from direct energy use within a community are accounted for, but imported electricity are not, which is significant in most US cities. Thus both (Brown, Southworth, & Sarzynski, 2009) and (Parshall et al., 2010), provide a partial accounting of in-boundary energy use and associated GHG emissions.

In (Sovacool & Brown, 2010), the authors inventoried geographic-based GHG emissions of 12 international metropolitan areas. The study covered energy use in buildings (residential, commercial, industrial), road transport, agriculture within the boundary, and waste – accounting for almost all in-boundary GHG emissions, non-energy processes were not accounted however. No trans-boundary activities were accounted.

The city of Denver, Colorado is the first known city to have included trans-boundary GHG emissions in their community-wide GHG emissions estimates (Greenprint, 2007), as was published and articulated by Ramaswami et al. (2008). The method accounted for all in-boundary emissions, and included trans-boundary emissions from airline travel, fuel refining, water/wastewater treatment, and production of cement & food for in-boundary use.

There are two known studies to have accounted for GHG emission for Los Angeles (Ngo & Pataki, 2008), and Chicago (McGraw, Haas, Young, & Evans, 2010), respectively. Both accounted for a comprehensive set of in-boundary emissions; the former included trans-boundary emissions from food production and wastewater treatment, whereas the latter did not cover these categories, but did account for freight.

In a study of ten global cities, Kennedy et al. (2009) inventoried GHG emissions from electricity, heating & industrial fuels, industrial processes, road transport, aviation, marine, and waste, in a method that fully accounted for in-boundary GHG emissions. Lifecycle, upstream emissions from refining the fuels used within each city were the trans-boundary emissions considered. The authors cited the need to evaluate upstream GHG emissions from use of other critical materials in cities (e.g. food, buildings materials, etc.), which is now being addressed.

Hillman and Ramaswami (2010) developed an approach that accounted for in-boundary GHG emissions, plus lifecycle emissions associated with key trans-boundary infrastructures serving cities: water/wastewater pumping & treatment, fuel refining, and embodied emissions from cement & food production, and commuter, air, and freight travel. Applying their method across eight US cities elucidated that the in-boundary plus trans-boundary accounting methodology provides a more holistic account of GHG emissions approaching national per person GHG emissions of 25 mt-CO_2e/cap for large US metro cities, with a presumed balance of carbon in remaining imports and exports. Very small cities with disproportionally low industrial activity were found to be outliers.

More recently, certain US states (e.g., Oregon; (Stanton et al., 2011)) and cities (e.g., King County, WA; (Stanton et al., 2012)) are embarking on full consumption-based approaches for GHG emissions footprinting that tracks trade of goods and services in and out of cities, i.e., all imports and exports. Such approaches based on economic IO have been used at national scales (Peters & Hertwich, 2008), but city-scale applications have been sparse due to challenges in downscaling IO data to the city level. Table 2-1 presents a summary of the above studies.

2.3 GHG Emissions Accounting and Footprinting Methods

As seen in the literature review in Table 2-1, there are three emerging methods for city-scale GHG emissions accounting. The three methods are Geographic boundary limited accounting, Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF), and Consumption-Based Footprint (CBF). This section discusses each of the three methods within the context of their theoretical origins, followed by their advantages & disadvantages. The discussion builds upon recent articles (Wright, Coello, Kemp, & Williams, 2011; Wright, Kemp, et al., 2011) who describe advantages & disadvantages of production & consumption based footprints, in general. In (Wright, Coello, et al., 2011) its acknowledged that city-scale footprints are in their infancy, making this research a timely addition by covering the newer TBIF method (not previously covered in (Wright, Coello, et al., 2011)) and providing city-specific data as illustrative examples. We begin by discussing the Geographic-Based Accounting.

Table 2-1: Differences in city-scale GHG emission footprints in peer-reviewed literature.

	In-Boundary Energy Use						Trans-Boundary Energy Use						
	Scope 1 (direct energy use & GHG emissions)					Scope 2 (indirect)	Scope 3 (indirect)						
							From Other Infrastructure Imports Serving Entire Community						From other Import-Export Trade Balance
	Res.	Comm.	Ind.	Non-Energy Proc. (e.g. waste)	Surface Transport	Electricity Imports	Water	Fuel	Cement	Food	Air Travel	Freight	
Brown et al. (2009)[a]	✓				Personal only	Residential only						✓	**Not usually considered in geographic approaches**
Parshall et al. (2010)[a]	✓			✓	✓							unclear	
Sovacool and Brown (2010)[a]	only where available			✓	Personal and Mass Transit	✓				✓			
Ramaswami et al. (2008)[b]	✓			✓	✓	✓	✓	✓	✓	✓	✓		
Ngo and Pataki (2008)[b]	✓			✓	✓	✓	✓			✓			
McGraw et al. (2010)[b]	✓			✓	✓	✓						✓	
Kennedy et al. (2009)[b]	✓			✓	✓	✓		✓			✓		
Hillman and Ramaswami (2010)[b]	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	

Focus of analysis: a) Geographic; b) Trans-Boundary Infrastructure Footprint (TBIF) inclusions; Res.= Residential; Comm.= Commercial; Ind.=Industrial; Non-Energy Proc.=Non-Energy Processes.

2.3.1 Geographic-Based Accounting

Boundary limited geographic approaches to GHG emissions accounting are those used in national inventories, which are largely considered “production-based”, even though they include fuel combustion GHGs by final consumption (i.e., in homes, and personal vehicles, etc.). In other words, this method accounts for GHG emissions from all production activities within the nations geopolitical boundary, although direct GHG emissions from end-use of energy in households are also included. These national GHG accounts are typically related to metrics of productivity, particularly Gross Domestic Product (GDP), and illustrated as GHG/$GDP (EPA, 2010). Purely geographic-based is not suited per se for reporting GHG/person; in order to truly represent an individual’s impact on global GHG emissions, carbon embodied in trade to and from the country (imports/exports) must be included. For larger nations such as the US, about 90% of GHG emissions resulting from in-boundary production are consumed within the boundary, and net import GHG emissions (imports less exports) are about 7% of the country’s GHG emissions (Peters & Hertwich, 2008). Therefore, strictly geographic and consumption-based methods may be numerically similar for large countries or populations. However, strictly geographic approaches are not really suited for small cities because many of their infrastructures (e.g. transport networks, power plants, etc.), extend well beyond the city. For example, more than 60% of workers in Denver commute from other cities in the region (Ramaswami, et al., 2008), electricity transmissions can exceed 200 miles in the US (Hirst, 2000), while freight travel averages 600 miles (BTS, 2009), and US food travel averages 1,500 miles (Weber & Matthews, 2010).

2.3.2 Trans-Boundary Infrastructure Footprint (TBIF)

The Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF) is an innovative method developed by Ramaswami et al. (2008) which recognizes that cities are not like large nations, in that energy use to provide essential infrastructures like electricity, fuel, etc., often occurs outside the geographic boundary of the city. The TBIF method therefore borrows from the concept of Scopes used in corporate GHG accounting (described previously in the introductory section), to account for essential trans-boundary infrastructures serving cities. The method can be thought of as an infrastructure based supply-chain footprint for cities, accounting for GHG emissions from buildings infrastructures (residential, commercial, and industrial) within the city (Scope 1) and trans-boundary electric power supply, trans-boundary transportation (road, air, and freight), fuel supply, water supply, waste management, and construction materials infrastructures serving cities (Scopes 2 & 3). See Table 2-2.

Table 2-2: Trans-boundary infrastructure activities accounted for by the TBIF.

Energy Use and Direct GHG Emissions within the Boundary (Scope 1)	Energy Use in Various Trans-boundary Infrastructure Sectors Serving Cities (Scopes 2 & 3)
Buildings Infrastructure – Direct Fuel Combustion and GHG Emissions From: • Residential Buildings • Commercial Buildings • Industrial Facilities	**Energy Sector**: • Electric Power Production • Fuel Refining **Water and Waste Sector**: • Water Supply pumping • Water & Wastewater treatment • Landfill emissions from waste disposal **Construction Sector**: • Cement Production • Supply chain of other major materials to cities **Transportation Sector**: • Air Travel • Long Distance Freight **Food Production**

Sample Results & Policy Impact: Results from applying the TBIF method to the City and County of Denver are shown in Figure 2-1. TBIF results shown in Figure 2-1 were obtained using bottom-up end-use of electricity and natural gas for buildings within the city, obtained from the local utility's billing data. Energy use in surface transportation was computed using regional vehicle miles traveled (VMT) across the commuter-shed, and allocated to Denver based on origin-destination of trips. Emission Factors (EF) of energy carriers were consistent with IPCC. Often, material and energy flows (e.g., energy use in air travel, cement use in city) were obtained from local data such as airports or economic census. EFs relating to the embodied energy of materials were obtained from regional scale LCA (for cement) and national EIO-LCA (for food production), as discussed in Ramaswami et al. (2008) and Hillman and Ramaswami (2010). Results show GHG from the buildings sector corresponded to about 51% of which Scope 2 electricity related GHG emissions are 36%, while GHG emissions from surface transport tailpipe emissions were about 19%. The additional Scope 3 emissions (hatched) were attributed to trans-boundary activities such as air travel, fuel processing, cement production, and food production. With these inclusions, Denver's GHG emissions footprint approached a broader GHG footprint that is in-line with the national average per person GHG emissions of 25 mt-CO_2e/person, suggesting the method is effective in capturing dominant trans-boundary emissions associated with Denver. Similar convergence with national scale was seen in 6 other large US cities (Hillman & Ramaswami, 2010).

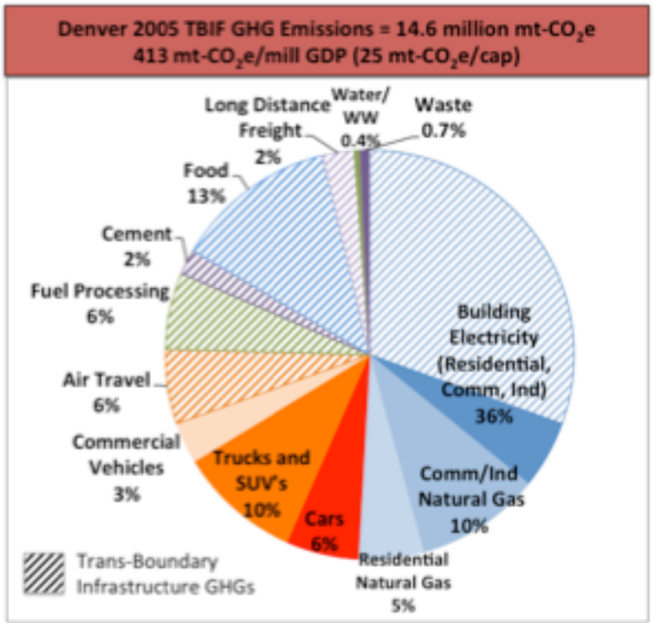


Figure 2-1: Trans-Boundary Infrastructure Footprint (TBIF) for Denver, Colorado.

The TBIF method has been shown to be highly policy-relevant, resulting in innovative actions taken by the city (Hillman & Ramaswami, 2010; Ramaswami, et al., 2008). In addition to focusing in on energy efficiency and conservation within the boundary, cities are now also able to focus on cross-scale infrastructure efficiencies, e.g., related to water supply, regional transport, and the materials supply chain, etc. For example, Denver using the TBIF method, has implemented a green concrete policy aimed at reducing GHG embodied in concrete with the use of fly ash substitution for cement. Denver is also conducting a pilot project to evaluate conversion of food waste to energy. As a result of the TBIF method, cities such as Denver (in 2007) and more recently San Francisco (in 2009) have developed voluntary travel offset programs at their airports (Cabanatuan, 2008). Cross-sector strategies such as tele-presence that can displace airline travel are also particularly amenable for accounting in the TBIF method, wherein the trade-offs between buildings energy use for tele-conferencing programs can be shown to offset airline travel emissions. Lastly, as seen in Figure 2-2 (a-b) and in Table 2-3, the TBIF method can be used in tracking GHG emissions over time, which further emphasizes the illustration of trade-offs.

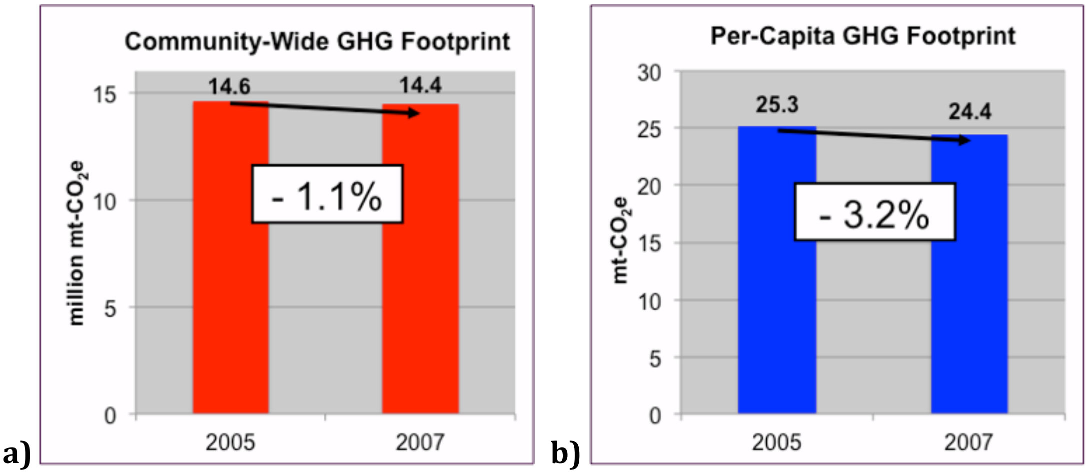


Figure 2-2: TBIF Footprint for Denver, CO. 2005 and 2007.

Table 2-3: Demographic and Per Person Use trends in Denver, CO. Annual % changes are calculated from 2000-2007.

Demographic Trends			Per Person Use		
Measure	**Annual % Change**	**Data Source**	**Measure**	**Annual % Change**	**Data Source**
Population	+ 0.95%	U.S. Census	Electricity	+ 0.9%	Xcel Energy
New Home Stock	+ 1.26%	CCD Assessor	Natural Gas	- 1.36%	Xcel Energy
New Comm. Area	+ 0.19%	CCD Assessor	Motor Gasoline	- 0.7%	DOR
			Diesel	+ 1.2%	DOR

CCD: City and County of Denver; DOR: Colorado Department of Revenue.

Advantages: The primary advantage of the TBIF method is that all activities within the city, residential, commercial, and industrial, are considered together, along with the trans-boundary infrastructures critical for these activities. See Figure 2-3. Thus the method is relevant for city and regional planners who consider transport, power, water and materials supply in the region, as a whole. The manner in which the TBIF method addresses trans-boundary infrastructures serving the entire community is illustrated schematically in Figure 2-3.

Thus the advantages of the TBIF are concisely shown as (Ramaswami, Chavez, Ewing-Thiel, & Reeve, 2011):

- Relevant to city and regional planning for whole communities – considering residences, businesses and industries together.
- Well suited for showing impacts of infrastructure changes, linking local and regional actions.
- Cross sector strategies, such as teleconferencing are visible.
- Easy for public communication in that the major activities in home carbon calculators (e.g. airline travel etc.) are now also included in city accounting.
- The method yields sector-specific benchmarks developed for each city, useful for comparing sectoral efficiencies across cities.

- The method is effective for tracking climate change impacts such as urban heat island effect that relate to direct in-boundary Scope 1 fuel combustion
- Metrics pertaining to risk, vulnerability, and adaptation, can be quantified for both in-boundary infrastructures (e.g., urban heat island) and trans-boundary supply chain risks (e.g., risks to a city's electricity system due to climate-water impacts).
- The method is particularly useful in linking local Scope 1 GHG emissions with local health impacts, e.g., increases in local ozone concentration (Jacobson, 2010), and in potential future inclusions of short-lived climate forcers (SLCF).
- As shown in figure 2, the TBIF method used locally specific data and is suitable for tracking a city's GHG emissions over time.

Indeed with its capacity to address local health impacts of GHGs and SLCF, and provide input on supply chain vulnerabilities, the TBIF method is well suited to address both GHG emissions and climate adaptation in cities.

Disadvantages: The primary shortcoming of this method is that it requires improved metrics for inter-city comparisons on a consistent basis. Because the TBIF method is based upon geographic production-based inventories, the often used per capita (same as per resident) metric is not appropriate for inter-city comparisons using this method, particularly when a city with high industrial-commercial activity is compared with a solely residential community. GHG per unit gross regional product (or gross metropolitan product) is likely a better option, but for many smaller cities and towns such data are not reported. In such cases, normalizing community-wide emissions by residents plus jobs could be an alternate for comparing cities. Per capita GHG emissions for this method may also be used if a typology of cities is created, representing producer-, consumer- and energy-balanced cities, such that cities are only compared within their peer group. These are explored and discussed in a forthcoming chapter.

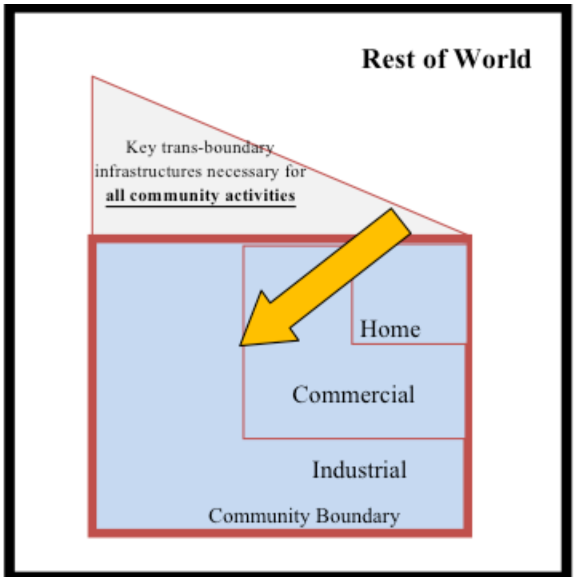


Figure 2-3: Illustration of TBIF for any community.

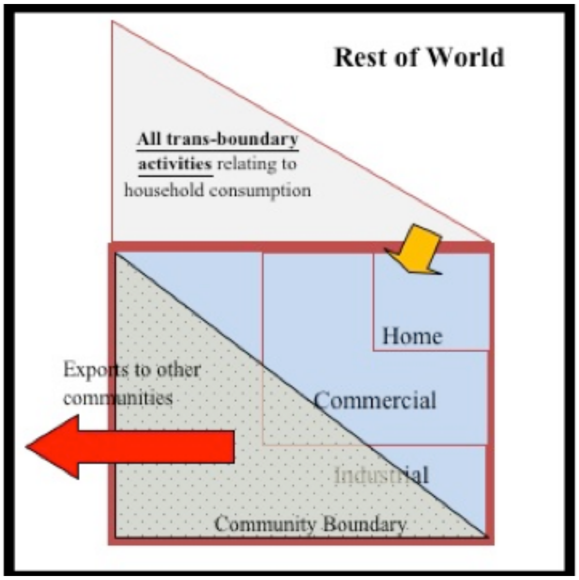


Figure 2-4: Illustration of CBF for any community.

2.3.3 Consumption-Based Footprint (CBF)

The consumption-based approach accounts for global GHG emissions resulting from economic final consumption (households, government, and capital investments), within a city, including GHG emissions in imports, but excludes GHG from the production of exports within the boundary. This method traces GHG emissions fully upstream, outside of the community boundary, accounting for all trans-boundary activities that serve economic final consumption in the community. Of the economic final consumption sectors, households have been estimated to be responsible for the vast majority of the consumption (Weber & Matthews, 2008) (i.e. 80% final demand in the US), thus the method becomes well suited for evaluating household impacts on GHG emissions. A schematic showing activities in a typical consumption-based application can be seen in Figure 2-4. Its been recognized there are two general approaches for conducting CBF for cities.

The two CBF approaches are Consumer Expenditure Survey (CES), and Input-Output (IO). The CES approach assesses the impacts of household consumption, only, linking purchases by households from a number of goods and services to economic sectors (i.e., North American Industry Classification System (NAICS)). While direct energy end-use and associated emission factors are applied from local (territorial) data, GHG emissions from all other purchases apply national average production emission intensities – regardless of production location (Jones & Kammen, 2011; Weber & Matthews, 2008). Because CES' report on aggregate household consumption, the approach is not equipped to inform on the true location of production. The aggregate household GHG emissions are normalized per households or per capita, yielding CBF from CES.

The other approach to CBF is the economic input-output (IO) approach. In this application national IO tables are downscaled (also called *regionalized*) to counties, creating consumption profiles that address all components of final consumption (households, government, and business investments). Such an approach, which is often referred to as a *non-survey* approach for its use of national statistics, has been made commercially available by IMPLAN, Inc. for every US county. However, the accuracy of downscaled IO tables in representing material and energy flows in cities remains to be explored. Note that the IO approach for CBF has been adopted in this thesis.

Sample Results & Policy Impact: The preliminary GHG emission results from final consumption in Denver were computed using commercially available downscaled IO data from IMPLAN. IMPLAN estimates monetary transactions and expenditures throughout the local economy across 440 economic sectors. The monetary expenditures for Denver were then converted to GHG emissions using a single region model and GHG emissions by economic sector (in mt-CO_2e/million$) from the EIO-LCA tool (CMU, 2008).

The total life-cycle emissions associated with final consumption can be separated to show the contribution by scope, i.e., in-boundary fuel combustion (Scope 1), electricity imports (Scope 2), other infrastructure imports denoted in TBIF (Scope 3). The other represents GHGs occurring while fulfilling all other goods and services to meet final consumption.

Advantages: The primary policy relevance of this method is that it makes the full trans-boundary impact of household consumption visible. Because most of the final consumption comes from households, this is theoretically the most rigorous method for comparing per person GHG emissions from household expenditures. Further, the method can help inform greening of government operation supply-chains. With detailed and accurate IO data, imports and exports to/from a community can be traced. Overall, an IO approach to life cycle assessment has been recognized as one producing fast, holistic, and mostly acceptable results. Although the approach must be completed with caution as large variances may exist across scales (Hendrickson, Horvath, Joshi, & Lave, 1998).

Disadvantages: However, the full consumption-based IO method is valuable only if accurate IO analysis and data are available at the city scale. Misallocations in local IO tables can occur when physical flows of energy and materials do not match the flow of economic activity; often occurring when large corporate headquarters in a city report economic activity well outside city boundaries. For many US cities, IO data are not published at a scale smaller than the county scale (now also available at the zip code level). Unlike the TBIF, the CBF divides the community in two, with commercial-industrial activities for exports not included in the unit of analysis. See Figure 2-4. For some communities (e.g. resort towns & industrial towns), this excludes a sizable portion of their local economy that could be shaped by local policies. The application of IO tables for GHG emission accounting is new at the city level, and researchers are learning about its application to smaller spatial scales where downscaling national data poses challenges.

The difficulty of tracking GHG emissions via this method is triggered by the low publishing frequency of national IO tables; at every 5-7 years for the U.S.

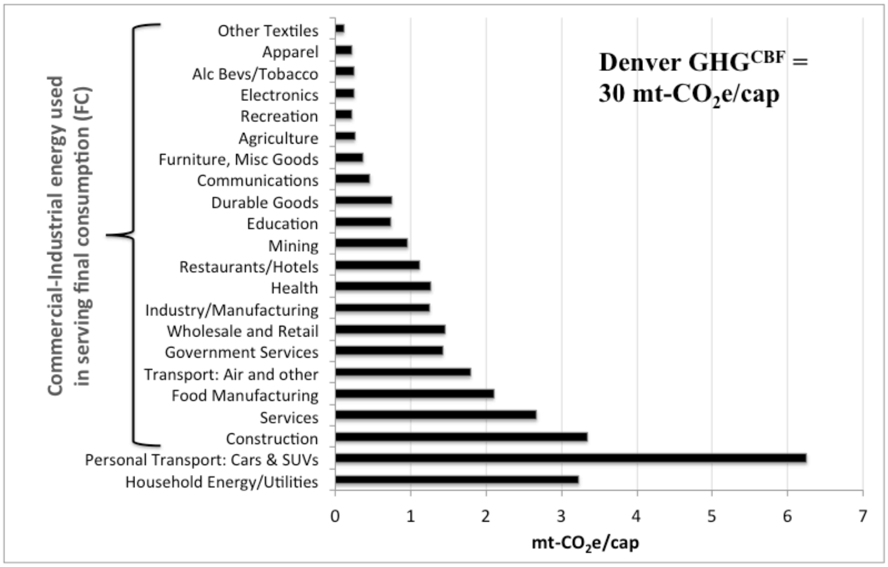


Figure 2-5: Denver CBF GHG Emissions. Preliminary Results.

2.4 Update on Protocol Development

In summary and as seen in Figure 2-3 & Figure 2-4 and in the discussions in this chapter, the TBIF and CBF are two different approaches which give distinctly different estimates of a communities GHG emissions, and inform policies differently. The TBIF method accounts for all in-boundary emissions within the geographic boundary of a city, along with key trans-boundary infrastructures serving the community as a whole. The method is suited to future infrastructure planning that addresses the whole community, and to address regional cross-scale and cross-infrastructure strategies across city boundaries. CBF GHG emissions accounts for all (in-boundary and trans-boundary) GHG emissions resulting from economic final consumption in the community, while the in-boundary commercial industrial activities exported elsewhere, along with their supply-chains, are excluded, even though these local activities generate jobs and may also be shaped by local regulations. The method is especially suited to educate households about the global nature of their consumption.

Recognizing that both methods provide useful and different information, ICLEI-USA has published a *draft* framework for community-scale GHG emissions accounting and reporting (ICLEI, 2011). The framework aims to help local US governments in planning and demonstrating GHG emissions reductions, by establishing standardized approaches for which communities can use to create holistic baseline GHG emissions measures. Because the protocol is in development, it is subject to future revisions.

Recognizing that local governments have distinct reasons for measuring GHG emissions, the protocol has varying tiers of reporting. The reporting approaches for community-wide GHG emissions are Basic Reporting Standard (Basic), Expanded Community Impact Reporting (Expanded), and Consumption-Based Reporting. The below schematic illustrates the ICLEI reporting framework, and how it links with the methodological approaches described in this chapter. The basic reporting standard is expected to describe a minimum level of inclusions for community GHG emission accounting to establish consistency across cities. The expanded community impact reporting provides guidance on measuring energy use and GHG emissions more holistically, by incorporating all key trans-boundary infrastructures as described in the TBIF method. Lastly, the protocol allows for an optional and separate accounting of GHG emissions from community final consumption using the CBF.

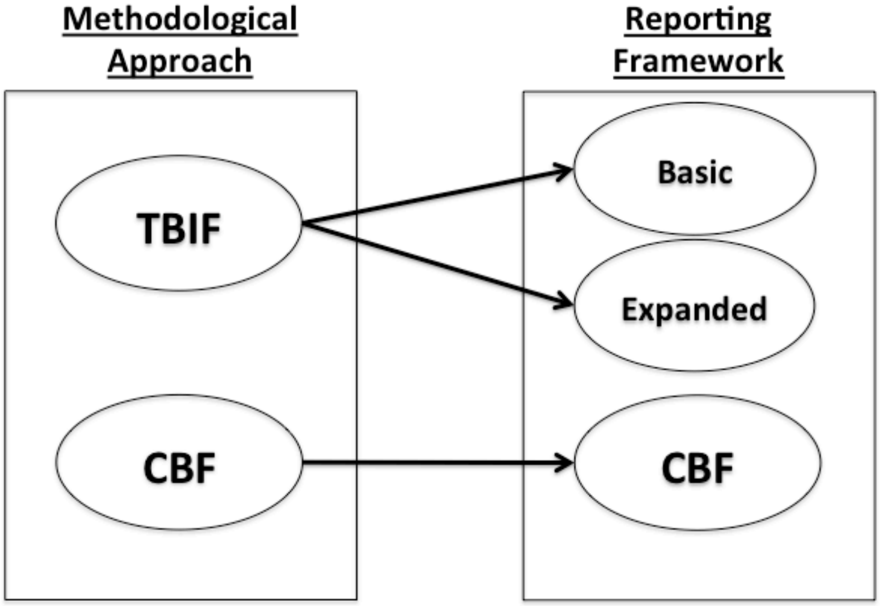


Figure 2-6: Link between GHG accounting approaches and ICLEI protocol.

2.5 Conclusion

Establishing a goal to develop low-carbon cities requires good measurement tools for GHG accounting in cities. While it is obvious that a low carbon city must improve the energy efficiency of its buildings and transport system within the boundary, this chapter asks – what other trans-boundary sectors are important in considering and defining a low-carbon city? Many of the sectors that are trans-boundary may in-fact offer further and more innovative opportunities for GHG mitigation – e.g., waste and industrial symbiosis and innovative technologies such as tele-presence. Changing the nature of consumption in communities, e.g., changing food-diets, also becomes a part of the low-carbon strategy toolkit. Recalling the adage – What Gets Measured Gets Done - measurements tools play a major role in shaping the available strategy set, and vice versa. Recent advances in trans-boundary GHG accounting Table 2-1, and the inclusions of such emerging knowledge into community-wide GHG protocols being developed by ICLEI-USA and others, is a major step in developing improved measurement tools.

The discussion presented in this chapter shows that one single metric (e.g., GHG/person) will likely not be suitable to represent GHG emissions associated with cities. A combination of variables such as GHG per unit city residents plus city employees, or the totality of economic output may all serve as potential metrics for defining a low-carbon city. In addition to aggregate citywide metrics, such as GHG/person or GHG/GRP, sector specific efficiency and consumption measures are also useful. Hillman and Ramaswami (2010) have quantified efficiency and consumption measures in buildings, transport, and materials sectors in cities, at no additional cost or effort beyond TBIF. Table 2-4 illustrates some of these efficiency metrics.

Table 2-4: Examples of city-scale energy and material efficiency metrics.

Sector	End Use Efficiency Metric
Household Energy Use	kWh/HH/mo, therms,/HH/mo, kBTU/HH/mo kWh/cap/mo, therms,/cap/mo, kBTU/cap/mo
Commercial Building Energy Use	kWh/sq-ft/mo, kBTU/sq-ft/mo kWh/GDP/yr, kBTU/GDP/yr
Community Transport	VMT/person/day, VMT/(residents+jobs)/day
Material Use	tons-MSW/capita/yr, mt-cement/capita/yr

Particular metrics will need to be ranked and weighted across cities. Efficiency benchmarks already existing in the literature (Ramaswami, et al., 2008) could be expanded on. It is likely to take a combination of various metrics, together, to help define a low-carbon city both for rigor and for policy-relevance (Zhou, Price, & Ohshita, 2010).

Other sustainability metrics such as health and well being, Amartya's Sen's concepts of human capabilities approach reflected in the Human Development Index (Anand & Sen, 2000), and emerging metrics of risk and vulnerability must also be considered in defining a low-carbon goal.

3. Mathematical Relationships and Methodology for Comparing GHG Emission Footprints

This chapter compares the policy relevance and derives mathematical relationships between three approaches for GHG emissions accounting associated with cities. The three approaches are: a) Purely-Geographic Inventory, b) Trans-Boundary Infrastructure Footprint (TBIF), and c) Consumption-Based Footprint (CBF). In a case–study of three U.S. communities (Denver Colorado, Routt Colorado, and Sarasota Florida), mathematical derivations coupled with data analysis shows that no one method provides a larger or more holistic estimate of GHG emissions associated with communities. A net-producing community (Routt) demonstrates higher TBIF GHG emissions relative to the CBF, while a net-consuming community (Sarasota) yields the opposite. Trade-balanced communities (Denver) demonstrate similar numerical estimates of TBIF and CBF, as predicted by the mathematical equations. Knowledge of community typology is important in understanding trans-boundary GHG emission contributions.

3.1 Introduction

Different types of greenhouse gas (GHG) emission footprints have been referenced in the literature, often referred to in shorthand as "carbon footprints". Technically, carbon footprints address only carbon dioxide (CO_2) and methane (CH_4) emissions, while GHG footprints address the global warming potential of all six Kyoto GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6), represented as CO_2eq (Wright, Kemp, et al., 2011). While these definitions are important, this chapter addresses the larger issue of *allocating GHG emissions* to various segments of societies – producers, consumers, nations and cities.

The assignment of GHGs associated with the full life-cycle of a product to a unit of production has been well-understood in the industrial ecology literature, e.g., (Eide, 2002). Recent efforts at the World Resources Institute (WRI) have incorporated life-cycle approaches to inform GHGs reporting by corporations (producers) using the concept of scopes (WRI, 2004, 2011).

Consumption-based footprints (CBF) have also been articulated, wherein GHGs in commercial and industrial sectors are not assigned to producers, but to economic final consumption represented by household expenditures, government expenditures, and business capital investments. At the national scale, GHG embodied in trade between nations has been assigned to final consumption activities in each nation, yielding CBF of residents in nations (Peters & Hertwich, 2008). More recently, downscaled input-output models at the scale of cities and states are being tested to develop CBF (Stanton, et al., 2011). Final consumption is dominated (>80%) by household expenditures; hence a large number of CBF studies have developed GHG footprints of households using readily available consumer expenditure data and tracing the full life-cycle GHG associated with these expenditures using EIO-LCA, e.g., (Jones & Kammen, 2011; Weber & Matthews, 2008).

When nations report GHG emissions, however, territorial accounting is employed, i.e., direct GHGs within national boundaries are reported in national GHG inventories, e.g., (EPA, 2010). These territorial accounts are often referred to as production-based accounts, but also include final household consumption of fuel (i.e., fuel combustion). Territorial accounts yield GHG intensity per unit productivity of nations, but are also reported on a per capita basis, although territorial GHG/capita does not reflect worldwide emissions associated with the residents of any nation.

There is wide recognition that strict territorial accounting of GHGs employed in national-scale GHG accounting is not meaningful for the smaller spatial scale of cities, e.g., (Kennedy et al., 2009; Ramaswami, et al., 2011; Ramaswami, et al., 2008). Cities are relatively small compared to nations, and also small compared to the larger-scaled infrastructure systems in which they are embedded, e.g., transportation commuter sheds, and power-supply networks. Consequently, important infrastructures serving cities that provision electricity, commuter travel, water supply, etc., are artificially truncated at the city’s geographic boundary. Thus, GHGs from energy use in these key trans-boundary infrastructures often occur outside the boundary of the city using these services (e.g., electricity used in a city is often generated outside of that city).

Several cities and associated research papers (see Table 3-1) have started incorporating the embodied energy in infrastructure supply-chains serving the city as a whole, an approach that is formally being articulated in this chapter as the Trans-Boundary Infrastructure Footprint (TBIF). TBIF studies have shown that energy use in key trans-boundary infrastructures serving cities can be as large, or larger than, the direct energy use & GHGs within city boundaries (Hillman & Ramaswami, 2010; Kennedy, et al., 2009; Ramaswami, et al., 2008).

The TBIF supports citywide cross-scale infrastructure planning for low-carbon cities addressing infrastructure supply-chains that serve both producers (e.g., industries) and consumers (e.g., households) that are co-located in a community, provisioning infrastructures (e.g., energy supply, commuter travel, etc.) to the community as a whole. Through these trans-boundary infrastructures, local- and higher-level governments are uniquely positioned to influence not only infrastructure-related household activities, but also infrastructure-related industrial-commercial production activities (e.g., energy efficient offices) in a city that may subsequently export goods/services elsewhere.

In contrast, CBF focuses more narrowly on city resident household- and government-consumption, examining their full supply-chain impacts worldwide. Increasingly, researchers are suggesting that both a TBIF and a parallel CBF be employed to inform a full spectrum of GHG mitigation strategies in cities (Baynes, Lenzen, Steinberger, & Bai, 2011; Ramaswami, et al., 2011). However, the two footprint approaches are often considered to be entirely separate, when in fact, they are mathematically related in important ways. Therefore the objectives of this chapter are to:

- Articulate the TBIF in the context of purely territorial and purely consumption-based accounting, addressing the policy relevance of all three approaches.
- Elucidate mathematical relationships between the three methods, enabling approximations and simplifications between them, as appropriate.

Table 3-1: Community-wide GHG emission studies in cities incorporating infrastructure supply-chains serving the whole community.

	Trans-Boundary Infrastructures Serving Whole Community						
Researchers	**Electricity**	**Water**	**Fuel**	**Cement**	**Food**	**Air Travel**	**Freight**
(Sovacool & Brown, 2010)	✓		✓				
Ramaswami et al. (2008)	✓	✓	✓	✓	✓	✓	
(Ngo & Pataki, 2008)	✓	✓			✓		
(McGraw, et al., 2010)	✓						✓
Kennedy et al. (2009)	✓		✓			✓	
Hillman & Ramaswami (2010)	✓	✓	✓	✓	✓	✓	✓
Baynes et al. (2011)	✓	✓	✓	✓	✓	✓	
Chavez et al. (2012)	✓	✓	✓	✓	✓	✓	
(Paris, 2009)	✓			✓	✓	✓	
(Sharma, Dasgupta, & Mitra, 2002a)	✓			✓	✓		

3.2 An Infrastructure-Based Supply-Chain Footprint for Communities

Trans-Boundary Infrastructure Footprints (GHG^{TBIF}) overcome the shortcomings of strictly boundary-limited approaches by using the WRI concepts of scopes described earlier. A TBIF for cities reports direct community-wide energy use and GHGs within city boundaries as Scope 1 emissions, GHGs from electricity generation for local use in all sectors (residential, commercial, industrial) as Scope 2 emissions, while trans-boundary life-cycle emissions associated with other essential infrastructures serving the community are incorporated as Scope 3 emissions.

Introduced by Ramaswami et al. (2008), TBIF quantifies Scope 3 GHGs from trans-boundary commuter- and airline travel, and from supply-chains providing drinking water, wastewater treatment, transportation energy, food supply, and building construction materials in cities. Hillman & Ramaswami (2010) added impacts from long-distance freight infrastructure. Baynes et al. (2011), and Chavez et al. (2012) have quantified supply-chains of electricity, water, fuel, cement, food, and air travel infrastructures serving the cities of Melbourne and Delhi, respectively. Several others incorporated upstream GHG emissions from a smaller subset of infrastructures (Table 3-1).

While studies have included different infrastructure supply-chain inputs, articulating the method explicitly as a *trans-boundary infrastructure supply-chain GHG emissions footprint* for cities, while elucidating its policy relevance, helps clarify the method. The infrastructures covered by TBIF are widely accepted as essential for any city to functioning through provision of water, energy, food, transportation, waste-treatment, and built environment materials (shelter). Developing trans-boundary GHG emissions footprints associated with these key infrastructures enables *multi-level governance*, (Betsill & Bulkeley, 2006) ranging from the city-scale (e.g., building codes) to the city-region (e.g., mass transit) to the state- and national-scales that set standards for electric power generation, transportation fuel standards, etc. Although the status of food production as an infrastructure sector is fuzzy, cities are considering structural changes that formalize “green infrastructure” for urban food production (J. Grimm, 2009). Moreover, food may also be viewed as another form of energy required by cities to be productive. Care must be taken to avoid double counting when incorporating GHG embodied in infrastructure supply-chains. For example, supply-chain GHG embodied in gasoline would double count with any oil refineries operating within the city. Most infrastructures are large and visibly distinct (e.g., oil refineries), that their GHGs can be carefully allocated based on use/demand.

In the case of food production, TBIF as modeled in this thesis is unique compared to other approaches. Most prior research has adopted the Bureau of Labor Statistics (BLS) Consumer Expenditure Survey (CES) (BLS, 2012a) as the source for the material flow analysis (MFA) of food consumed in a city. The CES reports economic expenditures for food consumption by homes, only, but does not reflect community-wide use. In this research the MFA of ‘Food’ represents true community-wide use by homes as well as all local businesses, obtained by tracking local & import interindustry flows and final consumption expenditures in IMPLAN (sectors 1-14). Another important detail is that the

GHGs from use of food incorporated agriculture/livestock portions, only (IMPLAN sectors 1-14), and not food manufacturing (IMPLAN sectors 43-69) such as the making of bread, beer, tortillas, etc. The reason for this is to keep from double counting the agriculture/livestock portions within food manufacturing. For example, supply-chain GHGs from Beer production within a community would also include the agriculture GHG from wheat, hops, rice, etc. Any small (limited) agriculture within the boundary can be carefully addressed avoiding double count (Chavez, Ramaswami, Nath, Ranjan, & Kumar, 2012).

Consumption-Based GHG Footprints (GHG^{CBF}) go beyond allocating infrastructure, to allocate the trade of *all* goods and services across cities, however, focusing only on supply-chains serving final consumption (see Figure 3-1). Thus, local commercial-industrial activities that produce goods and services for export elsewhere are allocated out, and excluded from the city's CBF.

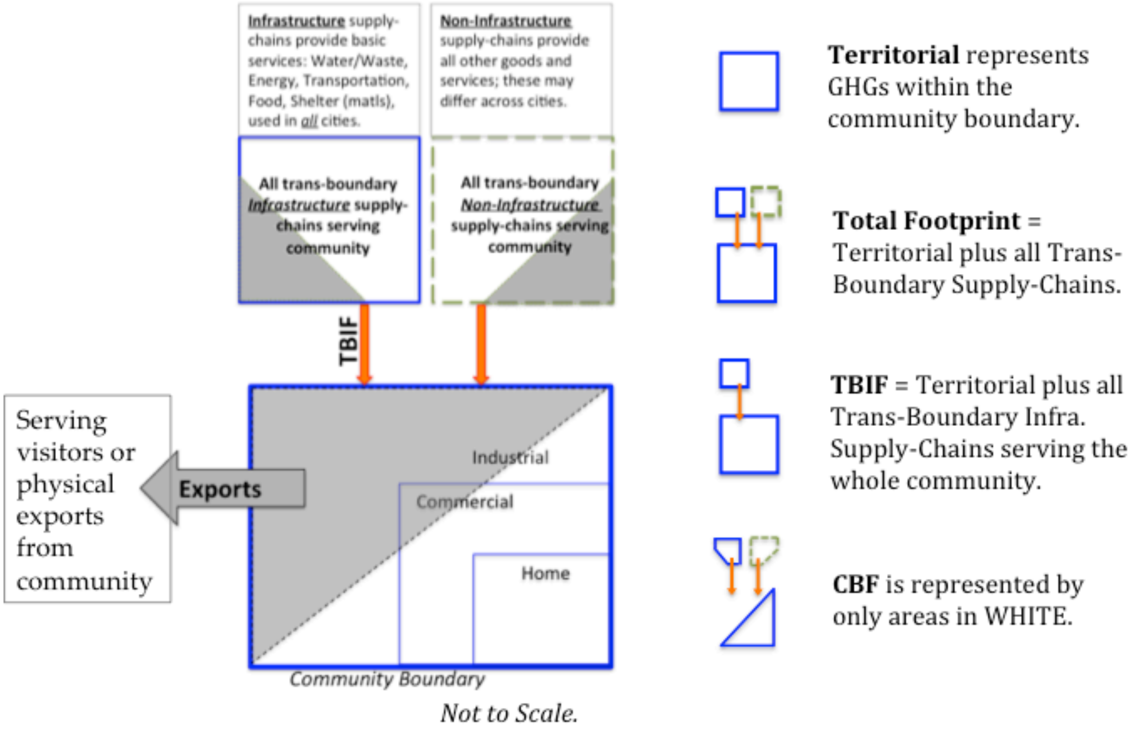


Figure 3-1: Schematic of Territorial, TBIF, and CBF approaches. Export related activities are shown in (gray/shaded).

Both TBIF and CBF provide different types of policy-relevant information. TBIF is particularly relevant to future infrastructure planning across spatial scales. The potential for greening of infrastructures and supply-chains, made visible by the TBIF, can be facilitated by multi-level governance from the city- to region- to state- and national-scales. For example, providing facilities for recharge/refueling of alternate fueled vehicles in cities requires government facilitation at all levels and LCA-based footprint computations to calculate net GHG benefits. TBIF is also very effective in addressing multi-scale risks that arise from fossil energy use by all sectors in a city – homes, businesses and industry. These risks range from indoor air pollution from poorly ventilated stoves in homes, to local-scale air pollution from traffic and industrial emissions, to regional haze and climate-change induced risks to a city's coupled water-energy system.

In contrast, CBF conceptually provides the most holistic assessment of per capita GHG emissions that fully reflects an individual's impact on global GHG. CBF informs households and governments of the full impact from their consumption activities, which can promote shifts in consumption patterns, as well as encourage purchases from cleaner producing regions, i.e., greening the supply-chain beyond the infrastructure sectors already addressed in TBIF. Because CBF excludes exported industrial-commercial output and their supply-chains (grey-shaded areas in Figure 3-1), the stimulus to greening the supply-chain is limited to households and governments. Table 3-2 summarizes the policy relevance of the purely geographic inventories, the TBIF, and the CBF.

3.3 Mathematical Relationships

TBIF and CBF are often treated as completely separate methods, when in fact they are mathematically related. This section highlights mathematical relationships between the two using a single-region IO (SRIO) model for simplicity of illustrating the derivation, followed by a uni-directional multi-region IO (MRIO).

Table 3-2: Policy relevant attributes and degree of relevance for each of the three GHG accounting methods. {* represents greatest relevance; [Explanations] are provided for reduced relevance}.**

Desired Policy-Relevant Attributes ↓	**Utility of Greenhouse Gas Accounting Methods to Policy Attribute {*** represents greatest relevance; [Explanations] are provided for reduced relevance}**		
	Purely Geographic	Trans-Boundary Infrastructure Footprint (TBIF)	Consumption-Based Footprint (CBF)
Informs future city & regional infrastructure (multi-level) planning and policy	* [Most infrastructures transcend city boundaries]	***	* [Excludes infrastructures serving local businesses and industries that export goods.]
Linkage of energy use to local urban heat islands, local air quality, and public health	***	** [Energy use in key infrastructures is allocated based on use, not location]	* [Energy use in all industries and businesses are allocated based on consumption, not location]
Informs supply-chain vulnerability for future planning	* [Most infrastructures transcend city boundaries]	***	* [Allocates GHG after consumption occurs, but does not address future planning for local supply vulnerability]
Enables Inter-city comparisons using per capita metrics to inform residents	N/A [Per capita metric is incorrectly applied]	N/A [Per capita metric is incorrectly applied]	***
Enables Inter-city comparisons using economic productivity metrics	* [Most infrastructures transcend city boundaries]	***	N/A
Data availability, quality and ability to benchmark or verify energy use and GHG emissions data	** [Remote sensing (e.g., Shepson et al., 2011) may enable independent verification]	**	* [IO models are calibrated to personal consumption and other data, not separately verifiable]

SRIO Derivation

The equation for computing consumption-based GHG emissions, GHG^{CBF}, is (Peters & Hertwich, 2008):

$$GHG^{CBF} = \underbrace{\left\{[B][L]+[EF^{use}]\right\}}_{\text{Life-Cycle/Supply-Chain GHG Emissions Intensity + Use Phase Emissions Factor}} \times \underbrace{\left\{[F]+[M_F]\right\}}_{\text{Total Final Consumption in Community}} \qquad \textbf{Equation 3-1}$$

where: **F** is the portion of local final consumption met by local production, and **M**$_\mathbf{F}$ is the portion of local final consumption met by imports. The sum of **F** and **M**$_\mathbf{F}$ yields total final consumption by households, government, and capital investments in the community. **L** is the Leontief Total Requirements Matrix *($-output/$-final demand)*, and in the SRIO model ***L*** is assumed to be equal to the national (U.S.) ***L*** matrix. **B** is the GHG intensity vector *(mt-CO_2e/$-output)*. **EF**$^{\mathbf{use}}$ is the use phase combustion emissions factor of fuels consumed by final consumption (e.g. natural gas, transport fuels). The production balance of an economy is written as:

$$\underbrace{[L]\left\{[F]+[E]\right\}}_{\text{Total Requirements (TR) of Final Demand}} = \underbrace{[L][M_Z]}_{\text{TR of Imports to Local Industries}}+\underbrace{[Z]+[F]+[E]}_{\text{Total Local Output (TLO)}} = [TLO]+[L][M_Z] \qquad \textbf{Equation 3-2}$$

where: **E** are community exports**,** **M**$_\mathbf{Z}$ are imports to local industries used in meeting final demand, and **Z** are local interindustry transactions.

Therefore, upon substituting the term **[L][F]** from Equation 3-2 into Equation 3-1, and recognizing that total net imports, **M**$_\mathbf{net}$, equals imports to local industry plus to final consumption less exports (**M**$_\mathbf{Z}$ + **M**$_\mathbf{F}$ - **E**), GHG^{CBF} in **(1)** can be re-written as:

$$GHG^{CBF} = \underbrace{\underbrace{[B][TLO]+[EF^{use}]\times\{[F]+[M_F]\}}_{\text{Represents Geographic (Territorial) GHG Emissions}}+[B][L][M_{net}^{\text{infra}}]}_{\text{Represents TBIF GHG Emissions Footprint}}+\underbrace{[B][L][M_{net}^{\text{non-infra}}]}_{\text{GHG embodied in net imports of non-infrastructures to city}}$$

Equation 3-3

where: Term 1, **[B][TLO]**, represent in-boundary GHG emissions from direct energy use in commercial-industrial production within the boundary serving final demand (includes exports).

Term 2, $\mathbf{[EF^{use}][F+M_F]}$, captures use-phase GHG emissions from final consumption, e.g., GHG from natural gas combustion by households. The sum of terms 1 and 2 yields GHG emissions from direct energy use, typically represented as Scope 1.

Term 3, $[B][L][M_{net}^{\text{infra}}]$, quantifies the lifecycle emissions from key infrastructures serving cities, including Scope 2 (electricity) and Scope 3 (other infrastructures) GHG emissions.

Term 4, $[B][L][M_{net}^{\text{non-infra}}]$, quantifies the lifecycle GHG emissions from all other, non-infrastructure sectors.

Note that M_{net}^{infra} $(= M_Z^{\text{infra}} + M_F^{\text{infra}} - E^{\text{infra}})$ represents net infrastructure imports (for electricity, natural gas and petroleum production, water/WW facilities, cement and food production-agriculture, air and freight transportation sectors), including imports to industry (M_Z) and to Final Consumption sectors (M_F), less exports (E). Likewise net non-infrastructure imports are represented as: $M_{net}^{\text{non-infra}}$ $(= M_Z^{\text{non-infra}} + M_F^{\text{non-infra}} - E^{\text{non-infra}})$. Note, since infrastructures provide basic services to all communities, their GHG contributions are being allocated based on use, prior to evaluating the net productivity of cities.

Note that:

$$\mathrm{GHG}^{\mathrm{TBIF}} = [\mathrm{B}][\mathrm{TLO}] + [\mathrm{EF}^{\mathrm{use}}] \times \{[\mathrm{F}] + [\mathrm{M_F}]\} + [\mathrm{B}][\mathrm{L}][\mathrm{M}_{\mathrm{Z}}^{\mathrm{infra}} + \mathrm{M}_{\mathrm{F}}^{\mathrm{infra}} - \mathrm{E}^{\mathrm{infra}}]$$

Equation 3-4

Substituting Equation 3-4 into Equation 3-3 yields the following relationship between $\mathrm{GHG}^{\mathrm{CBF}}$ and $\mathrm{GHG}^{\mathrm{TBIF}}$.

$$\mathrm{GHG}^{\mathrm{CB}} = \mathrm{GHG}_{\mathrm{Scopes1+2+3}}^{\mathrm{TBIF}} + \mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}}$$

Equation 3-5

Equation 3-5 implies that:

In a *trade-balanced* community, where $\mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}} << \mathrm{GHG}_{\mathrm{Scopes1+2+3}}^{\mathrm{TBIF}}$, $\mathrm{GHG}^{\mathrm{TBIF}} \approx \mathrm{GHG}^{\mathrm{CBF}}$.

In a *producer* community, where $\mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}}$ is a large negative, $\mathrm{GHG}^{\mathrm{TBIF}} > \mathrm{GHG}^{\mathrm{CBF}}$.

In a *consumer* community, where $\mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}}$ is a large positive, $\mathrm{GHG}^{\mathrm{TBIF}} < \mathrm{GHG}^{\mathrm{CBF}}$.

Complementary sets of equations for the MRIO analysis are presented next

MRIO Derivation

We now derive mathematical relationships between $\mathrm{GHG}^{\mathrm{TBIF}}$ and $\mathrm{GHG}^{\mathrm{CBF}}$ using a uni-directional MRIO model. A uni-directional MRIO assumes that direct trade to local industries dominates. For details on uni-directional MRIO, the reader is referred to (Lenzen, Pade, & Munksgaard, 2004; Peters & Hertwich, 2008; Weber & Matthews, 2008)). MRIO attempts to attribute impacts to a particular region by considering a number of trade partners with different production characteristics (i.e., L-matrix). For simplicity, we begin by writing MRIO $\mathrm{GHG}^{\mathrm{CBF}}$, using a two-region model where Region 1 is the local community, and Region 2 is the rest-of-world (ROW).

$$GHG^{CBF} = [B][L_1][F] + [B][L_2][M_F] + [EF^{use}][F + M_F]$$ **Equation 3-6**

where: $\mathbf{L_1}$ = $(I-A_1)^{-1}$ = $(I-[A_{11}+A_{21}])^{-1}$ and is the full production matrix of the local/base economy, $\mathbf{L_2}$ is the ROW production matrix in which following uni-direction MRIO, is assumed equal to the national (US) production matrix ($\mathbf{L}$).

The production balance of an economy in the MRIO framework is written:

$$[L_1]\{[F] + [E]\} = A_{11}x_1 + A_{21}x_1 + F + E = TLO + A_{21}x_1$$ **Equation 3-7**

where: $\mathbf{A_{11}}$ are the direct requirements on local production, $\mathbf{A_{21}}$ are the direct requirements on production of industrial imports from region 2 to 1, and $\mathbf{x_1}$ is region's 1 output. Further, $A_{11}x_1 = Z$, and $A_{21}x_1$ equals the total industrial imports into the local economy, region 1.

Next we assume that all industrial imports into region 1 are exclusive of region 1 exports, and that $\mathbf{A_{21}x_1 \approx [L_2][M_Z]}$. Then, upon substituting $\mathbf{[L_1][F]}$ from Equation 3-7 into Equation 3-6, MRIO GHG^{CBF} are shown as:

$$GHG^{CBF} = [B][TLO] + [EF^{use}][F + M_F] + \{[B][L_2][M_Z^{infra} + M_F^{infra}] - [B][L_1][E^{infra}]\} + \{[B][L_2][M_Z^{non-infra} + M_F^{non-infra}] - [B][L_1][E^{non-infra}]\}$$

Equation 3-8

where,

$\mathbf{[B][TLO]+[EF^{use}][F+M_F] + \{[B][L_2][M^{infra}] - [B][L_1][E^{infra}]\}}$ should approximate GHG^{TBIF}, and

$\mathbf{\{[B][L_2][M^{non\text{-}infra}] - [B][L_1][E^{non\text{-}infra}]\}}$ are the GHG embodied in net imports of non-infrastructures to the city.

These relationships can be directly related to those obtained from Equation 3-5.

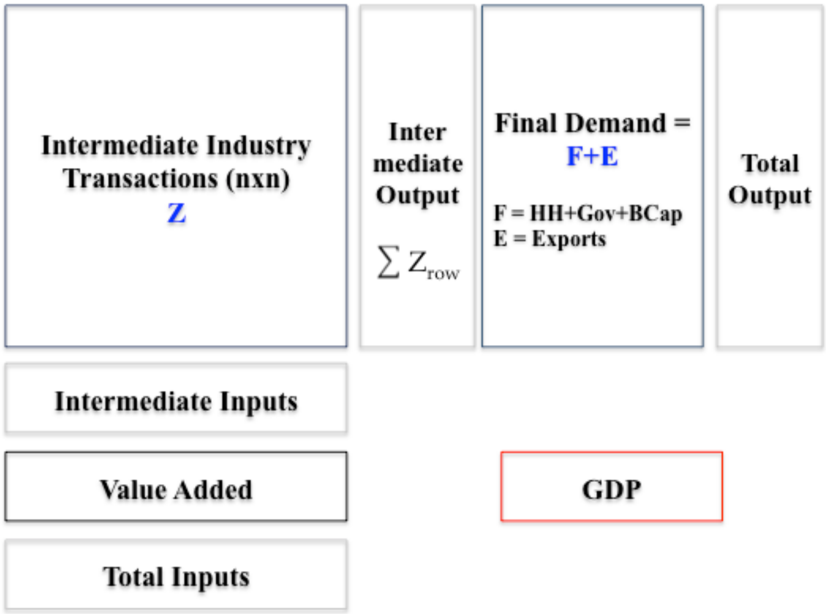


Figure 3-2: Basic representation of an economy through economic input-output (IO).

3.4 IMPLAN IO Regionalizing Method and Data Sources

There are two general approaches for constructing economic IO tables (Figure 3-2), 1) Survey (also known as Primary), and 2) Non-Survey (also known as Secondary). Survey approaches collect data on economy-wide transactions directly from businesses and other users within an economy. Even though survey approaches are thought to yield the most accurate representation of an economy, they are rarely completed due to the high level of resource requirements. An example of a survey approach is seen through the US benchmark IO table (BEA, 2008) compiled by the Bureau of Economic Analysis (BEA) and published every 7 years with a lag of the same (i.e., the benchmark IO table representing the US economy in 2007 will be released in 2014). On the other hand, non-survey approaches rely on publicly available data collected by others. Using non-survey approaches, an economy can be modeled in relatively short time, and with substantially less resources. IMPLAN IO tables are non-survey based, and make use of several data sources and techniques. The following summarizes the steps along with data sources used by IMPLAN in developing downscaled IO tables for US counties.

Employment statistics used in IMPLAN are derived from three sources, US Department of Labors' Covered Employment and Wages (CEW) (BLS, 2012b), BEA Regional Economic Information System (REIS) (BEA, 2012), and the US Census County Business Patterns (CBP) (Census, 2012b). CEW counts for those employees covered by unemployment insurance only, thus missing the self-employed and exempt industries (e.g., railroad). As a result, REIS data is used for estimating this additional employment in sectors such as agriculture, construction, and railroad, all of which are not subject to unemployment insurance. However, REIS data is only available at the semi-aggregated (3-digit NAICS). CBP is used to estimate government employment from national statistics, where CBPs employment statistics are based on first quarter employment. Note, employment data reported in IMPLAN are full and part-time employees. Employment statistics are used by IMPLAN for estimating county-level compensation, local outputs, and government & business capital expenditures.

Value Added consists of employee compensation, property type income, and indirect business taxes, which IMPLAN estimates as follows. Employee compensation (wage and salary income) is estimated using state-level income per employee ratios by sector (from REIS) multiplied by number of county employees in that same sector. Other property type income (OPTI) (payments from interests), and Indirect business taxes (IBT) (sales taxes) each are obtained from BEA's Gross State Product (GSP) (BEA, 2012) for each sector. State-level OPTI/income, and IBT/income ratios are multiplied with county income estimates for that same sector to compute county OPTI, and IBT, respectively.

Total Industry Output (TIO) is computed using national data from the BEA (BEA, 2011). National outputs are distributed to counties via national output per employee by sector, multiplied with the local employment for a particular sector.

Final Consumption (Households, Government Expenditures, and Capital Investments) are also gathered nationally, and distributed to counties as follows. HH expenditures are estimated from the diary and survey of the Consumer Expenditure Survey (CES) (BLS, 2012a), and distributed to counties based on number of households and income. Government expenditures are obtained from the Federal Procurement Data Center (FPDC), and the Annual Survey of Governments (state governments only). In its default form the FPDC is provided at the county scale, while the ASG is compiled nationally and is distributed to counties based on employment. Business capital investments use BEA Wealth, and the BEA Benchmark Workfile. Because capital investments are generally closely linked to construction activity, these national data are distributed to counties using local construction employment.

Trade (Imports and Exports) is estimated in the following manner. Foreign trade nationally are obtained from the US Department of Commerce Foreign Trade Statistics (USDOC, 2012), and distributed to counties through the ratio of local TIO to national TIO, by sector. Domestic trade between counties are estimated from IMPLANs National Trade Flow Model, which is a doubly constrained gravity model (Lindall, Olson, & Alward, 2005).

Table 3-3 presents a summary of data sources and techniques used by IMPLAN for estimating downscaled IO tables.

Table 3-3: Summary table of the data sources used by IMPLAN for construction downscaled IO tables.

Input-Output Table Element	Data Source	Technique for Local Distribution	Used for
Value Added	Salary Income: REIS Other Income & Taxes: BEA GSP	Income: from state-level Other Income & Taxes: from state GSP	Local GDP
Industry Output	BEA's output series	Local sector employment	Local TLO
Household Consumption	CES	Local households and income	Local household final consumption
Government Expenditures	FPDC, and ASG	FPDC by county; ASG via employment	Local government final consumption
Business Capital	BEA Wealth, and BEA Benchmark workfiles	Construction employment	Local business capital final consumption
Trade	Domestic: IMPLAN National Trade Model Foreign: USDOC	IMPLANs trade model is a gravity model. National USDOC thru local industry output.	Local Imports and Exports
Employment	CEW, REIS, CBP	Local data retrieved from data sources.	Derive TLO, Govt & Business Capital expenditures

3.5 Methodology – IO Table Calibration and GHG Footprint Computations

IO tables are not presently downscaled with the intent of being used for energy and GHG analysis, as being used here, and thus may be susceptible to misallocations that misrepresent energy use in communities, sub-nationally. To identify such instances, the following steps were implemented, and where required, the respective IO tables were updated/calibrated accordingly. Figure 3-3 is a high-level schematic of an economy, showing the energy sectors calibrated in our method. *C-I* is Commercial-Industrial; and *HH* is Residential (or household).

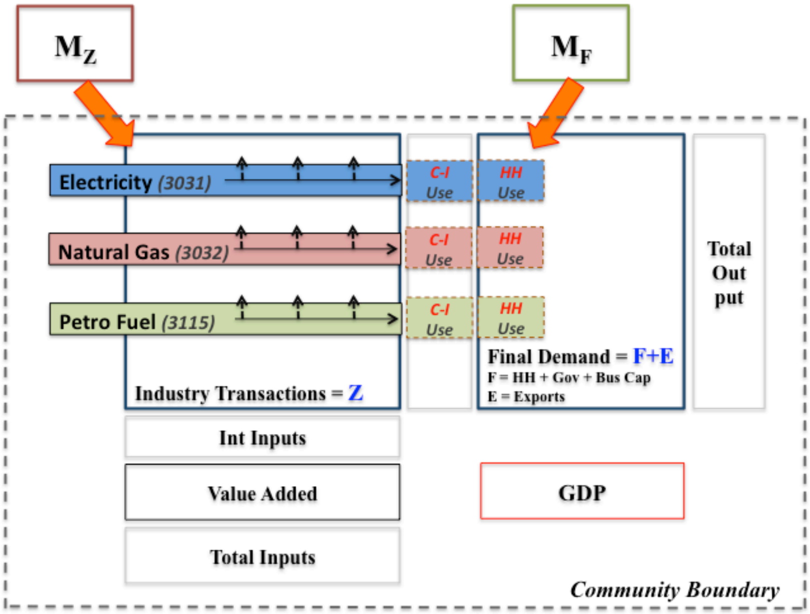


Figure 3-3: Schematic of basic IO table illustrating the energy sectors calibrated.

3.5.1 Method – IO Data Calibration

<u>Step 1 – Building Energy Use</u>: This step describes the calibration for community-wide electricity, and natural gas use.

<u>Retrieving from IO</u>: Building energy use reported in the default IO was obtained from the Z, F, M_Z, and M_F data files. Electricity is represented by IMPLAN sector 3031; Natural

Gas is IMPLAN sector 3032. Building energy used by commercial-industrial users is obtained from $Z + M_Z$, while residential from $F + M_F$.

Monetary IO expenditures were converted to physical units using state average prices for electricity, and natural gas, by end-user (residential, comm-ind) for the respective year (EIA, 2011). For example, the Colorado state average price for electricity in 2007 was 9.3 cents/kWh, and 6.8 cents/kWh for residential, and commercial-industrial, respectively (EIA, 2011). Electricity, and natural gas use from the unadjusted IO tables were then compared to geographic building energy use obtained from local data, separated by community-wide commercial-industrial, and residential use. Community-wide uses reported in the IO data for each (electricity & natural gas) are forced to match the amount retrieved from geographic data by manually adjusting Z & M_Z (commercial-industrial), and F & M_F (residential) in IMPLAN. For natural gas we maintain the local/imported proportion defined by IMPLAN. For electricity however, we simultaneously adjust community-wide use and the locally generated amount of community-wide use, as data to do so is available through eGRID. This is described in the following step.

This thesis does not repeat the specifics for adjusting & regenerating IMPLAN IO tables, as they are described elsewhere (MIG, 2004).

<u>Step 2 – Locally Generated Electricity</u>: The US EPA's Emissions & Generation Resource Integrated Database (eGRID) (EPA, 2011) was used to calibrate for the amount of community-wide electricity use that is locally generated. Locally generated electricity is estimated from the ratio of *Electricity Generation reported in eGRID,* by *total local electricity use* retrieved from local energy use data. In equation form:

$$\%locallygenelectricty_{comm-wide} = {eGRID_{county,gen}} \Big/ {totalelectricityuse_{localdata}} \qquad \textbf{Equation 3-9}$$

<u>Retrieving from IO</u>: Default IO values for locally generated electricity use were obtained as shown in Equation 3-10 for commercial-industrial, and Equation 3-11 for residential.

$$LocalGen_{Comm-Ind,default} = Z \Big/ \left(Z + M_Z\right) \qquad \textbf{Equation 3-10}$$

$$LocalGen_{res,default} = F \big/ \left(F + M_F\right)$$ **Equation 3-11**

In order to set the IMPLAN IO data to match the ratio computed from local data and eGRID (Equation 3-9), both Z and F were manually adjusted (IMPLAN sector 3031) before regeneration. At the point the adjustments are made to community-wide electricity use (step 1), and locally generated electricity (this step), the following balance holds.

$$eGRID_{county,gen} = \left(Z + F + E\right)_{3031}$$ **Equation 3-12**

Thus, if the *% locally generated electricity*>1 (Equation 3-9), then exports (E) (Equation 3-12) are greater than 0, as the community produces surplus electricity. Similarly, if the *% locally generated electricity*<1, then exports (E) are equal to 0, as the community requires electricity imports to fulfill local use.

Table 3-4 illustrates electricity generation for the three cities in this case-study (Routt, Denver, and Sarasota); where Table 3-4a compares the un-calibrated IMPLAN with eGRID, and Table 3-4b shows the calibrated values in IMPLAN along with community-wide electricity use for the three cities.

Table 3-4: Electricity generation for the three case-study cities. a) Local electricity generation: Un-calibrated IMPLAN vs. eGRID; b) Calibrated IMPLAN and community-wide use.

a)

Electricity Generation (in GWh)	**Routt, CO**	**Denver, CO**	**Sarasota, FL**
Z *(local interindustry)*	282	10,265	752
F *(local final consumption)*	121	3,616	912
E *(exports)*	877	5,415	7
Total Local Generation from *Unadjusted IMPLAN*	1,280	19,296	1,671
Total Local Generation from *eGRID*	3,654	1,269	0

% Error in local electricity generation between Unadjusted IMPLAN and eGRID	-65%	1,421%	Infinitesimal

b)

Electricity Generation (in GWh)	Routt, CO	Denver, CO	Sarasota, FL
Z *(local interindustry)*	251	957	0
F *(local final consumption)*	137	312	0
E *(exports)*	3,265	0	0
eGRID	3,653	1,269	0
M_Z *(imports to interindustry)*	0	4,081	1,860
M_F *(imports to final consumption)*	0	1,331	2,792
Total Community-Wide Use [a]	388	6,681	4,652

a. Total Community-Wide Electricity Use = $[Z+F]+[M_Z+M_F]$

Note, similar databases for other infrastructures were not identified; therefore such analysis was carried-out for electricity, only.

<u>Step 3 – Road Transport Energy Use</u>: This step describes the calibration for gasoline & diesel used in motorized road transportation.

<u>Retrieving from IO Data</u>: Fuel used in motorized road transportation reported in the default IO data was obtained from the Z, F, M_Z, and M_F data files. Petroleum Refining is represented by IMPLAN sector 3115. In this analysis it was assumed that all expenditures made from the petroleum refining sector were towards gasoline and diesel. Fuel used in road transportation by commercial-industrial users is obtained from $Z + M_Z$, while residential from $F + M_F$.

Fuel used in motorized transportation obtained from local data is allocated to users (residential, and commercial-industrial) using national statistics (DOE, 2009) which report that 96.8% and 3.2% of Gasoline is used by HH and non-HH users, respectively. The same data set also shows that HH and non-HH users use 7.5% and 92.5% of Diesel, respectively. State average gasoline and diesel prices (EIA, 2011) are used for the volume-monetary unit conversion for comparing IMPLAN and local data.

Community-wide uses of gasoline and diesel reported in the IO data are forced to match the amount retrieved from geographic data by manually adjusting Z & M_Z, and F & M_F in

IMPLAN for the total expenditures (gasoline plus diesel) for each commercial-industrial, and residential. We maintain the local/imported proportion defined by IMPLAN. Detailed steps for adjusting & regenerating IMPLAN IO tables are described elsewhere (MIG, 2004).

Step 4 – Sectoral Output: Sector outputs as reported by IMPLAN can be in error due to 2 factors: 1) when large corporate headquarters are situated in a city, or 2) when self-employed persons in a city operate energy assets (e.g., oil drills) located elsewhere. The effects of such scenarios are seen in a community's "exports", thus giving the illusion of highly producing sector(s). To identify some of these erroneous sectors, exports from each county were ranked by monetary value. Concentrations of top community sectors were validated through public information obtained from community web sites. For example, public sites confirmed economic specializations for Routt, CO (mining/electricity/entertainment/recreation). The physical condition for others, such as no Oil & Gas Mining in Denver, created a discrepancy with data reflected in IO tables. In such a case our approach zeroed the sector in question. In the future, better local data on local industrial outputs can yield more effective approaches to address these types of challenges. Appendix B shows top ten producing sectors, by exports, for the three cities.

Data on community imports is not readily available, making imports difficult to verify. Our approach thus relies on local knowledge stated above for identifying potential misallocations.

Step 5 – Adjusting IMPLAN Data File: After adjusting IMPLAN for the misallocations discussed in Steps 1-4, the respective IMPLAN file required regeneration in order to reconstruct all matrices. Recall that adjusted local uses of energy are visible in Z and F, and adjusted import values would be made in M_Z and M_F.

Below is a sample of how sectors may be impacted after such adjustments. Here we show a portion of these impacts through an example of Denver's electricity use (sector 3031), as illustrated via local use by households as well as the top five commercial-industrial sectors. eGRID shows that 19% of Denver's electricity use is locally generated. After calibrating local electricity use (Z & F), it's noted that the amount used as a percent remains constant (i.e., Real estate uses 21% of Denver's commercial-industrial local electricity).

Table 3-5: Unadjusted and Adjusted IMPLAN for locally generated electricity use in Denver. Use by households, and top five commercial-industrial users.

User	**Unadjusted Flow** (million $) *[91% locally generated]*	**Adjusted Flow** (million $) *[19% locally generated]*
Household	**$335**	**$29**
Commercial-Industrial (top 5)	**$665**	**$62**
Real estate buying and selling, leasing, managing, and related services	***$145***	***$13***
Oil and natural gas	***$82***	***$8***
Restaurant, bar, and drinking place services	***$41***	***$4***
Wholesale trade distribution services	***$29***	***$3***
Education from junior colleges, colleges, universities, and professional schools	***$20***	***$2***

3.5.2 Method – GHG Footprint Computation

After addressing the required calibrations, and after the adjusted IO table had been regenerated, the following methods were applied for estimating GHGs using the above SRIO equations.

Step 1 – Download IO Data: Final Consumption (F) is retrieved from ILCD (local), and M_F from INSM. Imports to local businesses & industries (M_Z) are retrieved from INDM. Exports (E) from the city are obtained from ILCD. Each is in the form of a column vector, in commodity basis. Note, Institution Local Commodity Demand (ILCD), Institution Imports (INSM), and Industry Imports (INDM).

Step 2 – Convert to Industry Basis: As the GHG intensity vector (B) is derived from the US benchmark IO table (industry basis), IO data (step 1) is converted from commodity basis (C) to industry basis (I) by multiplying each of the column vectors with the respective market shares matrix (MSM). MSM represents the proportion of a commodity that is produced by each industry, and is derived from the make matrix (IxC) by dividing each row by the total commodity output. IMPLAN automatically calculates MSM for each model.

Step 3 – Total Requirements: The column vectors, now in industry basis, are diagonalized creating a square (nxn) matrix, and multiplied by the total requirements matrix (L). Note, computing TLO is achieved by multiplying F and E, each, by the respective city's local L. All others are multiplied by the national L. Both local and national L are retrieved from IMPLAN. This step yields total outputs in current year prices (i.e., 2008 model yields outputs in 2008 prices).

Step 4 – Price Adjustment: As B is built from the 2002 economy, total requirements (step 3) are price adjusted to 2002$ using sector specific prices (BEA, 2009). Multiplying the ratio of $\$_{2002}/\$_{current}$ by the current year total requirements computed from step 3 yields the price adjusted outputs.

Step 5 – Computing GHGs: Lastly, multiplying the price-adjusted outputs with B yields GHG emissions attributed to each of the city's activities (e.g., F, M_F, M_Z, E).

3.6 Data Challenges

Computing the CBF and TBIF for the three communities presented in this chapter using downscaled IO data revealed significant data challenges in using IO tables. Downscaled IO tables are primarily used for economic development planning and are not specifically designed to match actual energy flows associated with electricity and fossil fuel use in local communities. Thus, several mismatches between monetary- and energy- flows were observed, summarized in Table 3-7.

Nationally downscaled home energy use did not match locally observed data and had to be corrected with the locally obtained data (Denver, 2010; Routt, 2010; Sarasota, 2008). Monetary energy purchases retrieved from IO tables were converted to physical units using state average prices by end-use sector (EIA, 2011). As seen in Table 3-7, the percentage of local electricity use that is locally generated as projected by IMPLAN, significantly exceeded the local electricity generated based on eGRID (EPA, 2011) in two of the three communities. For electricity, this mismatch became visible because comparison with eGRID was possible. Thus, city-scale IO model applications for GHG-accounting that espouse the ability to highlight supply chains within- versus outside the community may find that mismatches seen for electricity may also exist in other sectors, but remain unverifiable.

Other mismatches between monetary and physical flows were also observed when large corporate headquarters are situated in a city, or when self-employed persons in a city operate energy assets located elsewhere, as was found to be the case for Denver. For Denver, *Oil & Natural Gas Sector* (exports) and construction, generated exceedingly high economic activity caused by the entrepreneur residents and large headquarters located in the community, respectively. More collaboration with developers of IO models such as IMPLAN can help flag these mismatches and develop tools specific for city-scale energy use and GHG analysis, as the IO models are not currently designed to represent energy/material flows.

3.7 Results and Insights from Three City Analysis

The mathematical derivations (Equations 3-1 thru 3-5) are tested for three US communities, Denver Colorado, Routt Colorado, and Sarasota Florida. Downscaled IO tables for these three communities were obtained from IMPLAN and calibrated with actual household energy use, transportation energy use and commercial-industrial energy use reported in their respective GHG inventories (Denver, 2010; Routt, 2010; Sarasota, 2008). The calibrated IO tables had to be further corrected, after which Equations 3-1 thru 3-5 were evaluated; results are shown in Table 3-6.

Table 3-6: Results for TBIF and CBF for three U.S. communities.

County *(Typology)*	**GHG^{CBF}** ***(mt-CO_2e/cap)*: [eq. 1]; {eq. 3}**	**GHG^{TBIF}** ***(mt-CO_2e/cap)*** **[eq. 4]**	**Numeric ratio: GHG^{TBIF} of GHG^{CBF}**	**$GHG^{non\text{-}infra}_{Mnet}$ *** ***(mt-CO_2e/cap)***	**Comm-Ind Electricity use per capita** ***(kWh/cap)***
Routt, CO *(Net-Producer)*	[32.2]; {31.9}	52	163%	-20 Large negative **(Net-Producer)**	13,271
Denver, CO *(Balanced)*	[31.6]; {29.9}	28	94%	2 Approaches zero **(~Balanced)**	8,704
Sarasota, FL *(Net-Consumer)*	[28.8]; {29.7}	22	74%	8 Larger positive **(Net-Consumer)**	5,123
U.S. Average	28	26	93%	2 **(~Balanced)**	7,704

* **$GHG^{non\text{-}infra}_{Mnet}$** are the GHG embodied in net-imports of non-infrastructures

As expected, Equation 3-1 and Equation 3-3 yield estimates of GHG^{CBF} computed in two different ways that are in-line with each other for each of the three communities (column 2, Table 3-6). Moreover, GHG^{CBF} is also similar across the three communities, ranging from 29 mt-CO_2e/cap in Sarasota, to 32 mt-CO_2e/cap in Routt reflecting similar per household expenditures in the three communities. However, GHG^{TBIF} (computed from Equation 3-4) is vastly different across the communities, ranging from 22 mt-CO_2e/cap in Sarasota, to 52 mt-CO_2e/cap in Routt (column 3, Table 3-6) – the latter containing a high proportion of commercial-industrial activities engaged in exports.

The ratio of GHG^{TBIF} to GHG^{CBF} (column 4, Table 3-6) shows that Routt (163%) has a much larger GHG^{TBIF} relative to GHG^{CBF}, consistent with Equation 3-5 because Routt is a net-producing community after essential infrastructures are evened out (column 5, Table 3-6). For Sarasota GHG^{TBIF}<GHG^{CBF} since Sarasota is a net consumer, with its GHG embodied in non-infrastructure imports, $GHG^{non-inf\,ra}_{M_{net}}$, about 36% of GHG^{TBIF}. Meanwhile, for Denver $GHG^{TBIF} \cong GHG^{CBF}$, consistent with a trade-balanced community whose $GHG^{non-inf\,ra}_{M_{net}}$, is near zero (2 mt-CO_2e/cap), and also relatively small (7%) compared to GHG^{TBIF}. The last column in Table 3-6 shows the ratio of commercial-industrial electricity use normalized per resident - when compared to the U.S. average, this metric may be a suitable proxy to represent net-producing, net-consuming, or GHG trade-balanced communities.

Table 3-6 shows that establishing a typology of communities as net-producers, net-consumers, and trade-balanced in terms of GHG embodied in trade – after allocating basic infrastructures – is important in understanding the relative magnitude of the trans-boundary GHG contributions in different types of cities. Figure 3-4 shows the relationship across city types, where: Routt, a net-producing community reports $GHG^{TBIF} > GHG^{CBF}$, Denver, a larger metro community, estimated to be roughly trade-balanced reports $GHG^{TBIF} \approx GHG^{CBF}$; and Sarasota, a community dominated by residences (net-consumer) reports $GHG^{TBIF} < GHG^{CBF}$. Net-Producing communities have higher territorial GHG emission, and are served by relatively smaller trans-boundary supply chains. In contrast, highly consuming cities have smaller territorial GHG and much larger trans-boundary GHG.

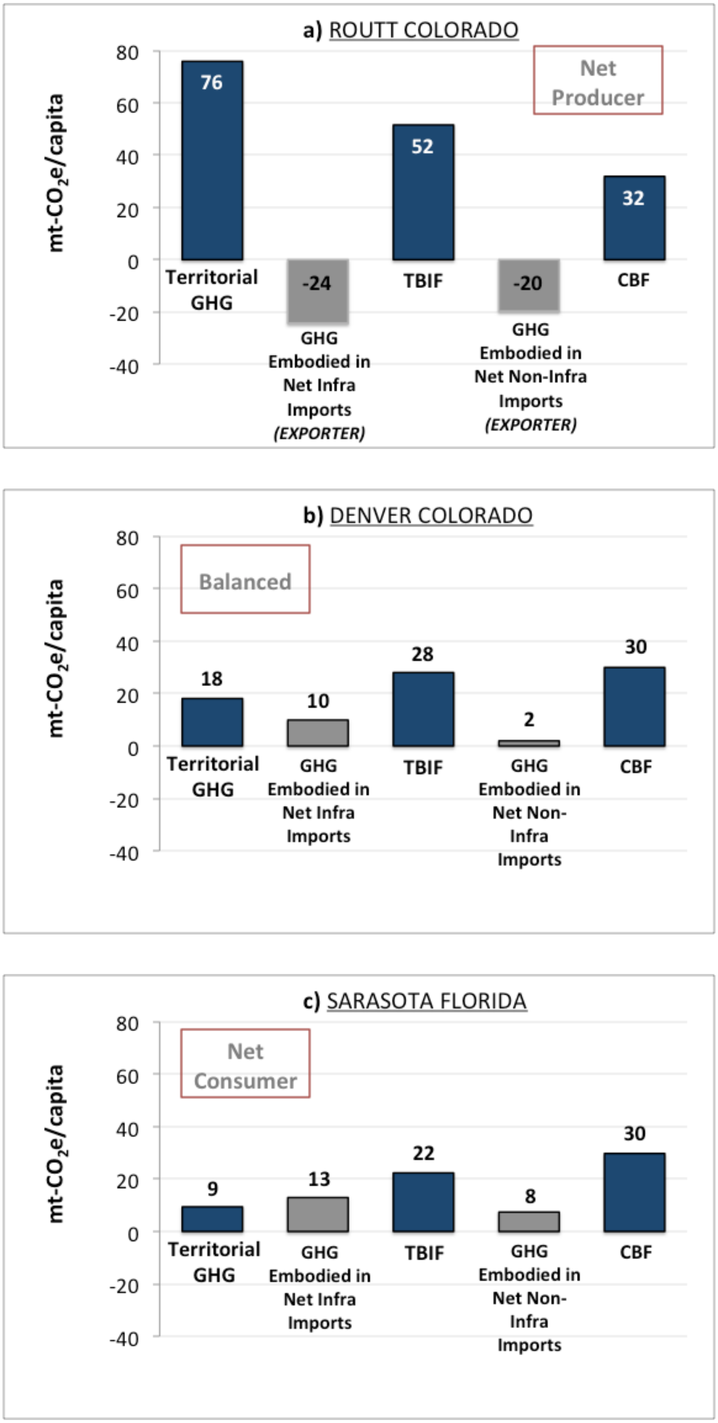


Figure 3-4: Illustration of relationships for GHG emission accounting derived in this thesis: a) Routt, CO; b) Denver, CO; c) Sarasota, FL.

Recall, Scope 1 are GHGs from end-use of fossil fuels with the boundary; Scope 2 are indirect GHG emissions from purchased electricity used in the community; and Scope 3 are all other indirect GHG emissions linked to the supply-chains for products used within the community. Also recall that CBF includes GHGs occurring while provisioning of final consumption, only, and excludes activities relating to exports. Thus, it is expected that in net-consuming communities a large portion of local activities (energy use and GHGs) be for the fulfillment of final consumption. Meanwhile, in net-producing and GHG trade balanced communities, where a larger portion of local activities fulfill exports, the opposite is expected – lesser portions of local activities in support of final consumption and greater towards exports.

The above is true among the three cities in this analysis. For Routt it is estimated that 22% of electricity, 33% of natural gas, and 40% of motor fuel used by local commercial-industrial users is for serving final consumption. For Denver it is estimated that 53% - electricity, 63% - natural gas, and 50% - motor fuel used by local commercial-industrial users is for serving final consumption. For Sarasota it is estimated that 63% of electricity, 76% of natural gas, and 85% of motor fuel used by local commercial-industrial users is for serving final consumption.

The following three figures highlight the differences described above. Each illustration shows GHG^{CBF}, by Scope, attributed to serving final consumption, only, for each of the three communities.

Figure 3-5 illustrates GHG^{CBF} for Routt (net-producer) by consumption category. Note that GHGs shown are a result from serving Routt's final consumption, only. Here we compute Scopes 1+2+3 serving final consumption equal 17.9 mt-CO_2e/cap (or 55% of CBF).

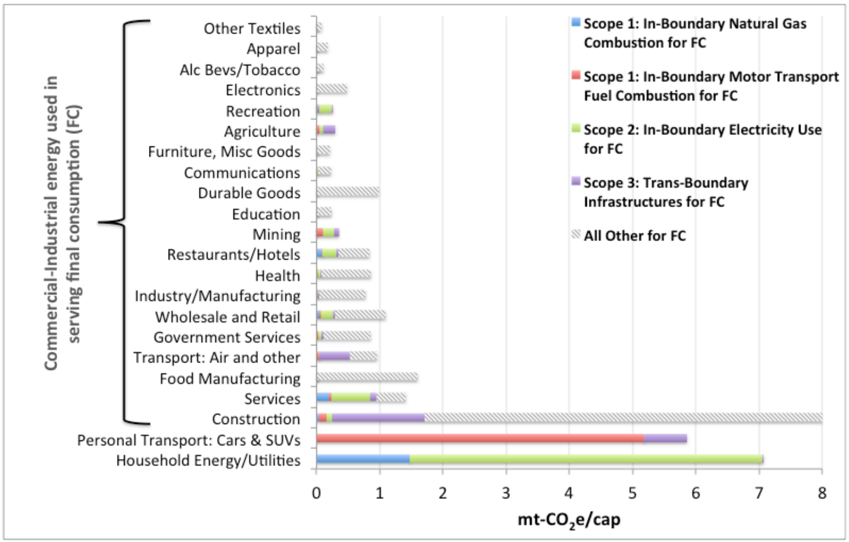


Figure 3-5: Routt – Illustrating GHG^{CBF} along with GHGs by Scopes in serving final consumption.

Figure 3-6 illustrates GHG^{CBF} for Denver (trade balanced) by consumption category. GHGs shown are a result from serving Denver's final consumption, only. For Denver we compute Scopes 1+2+3 serving final consumption equal 16 mt-CO_2e/cap (or 53% of CBF).

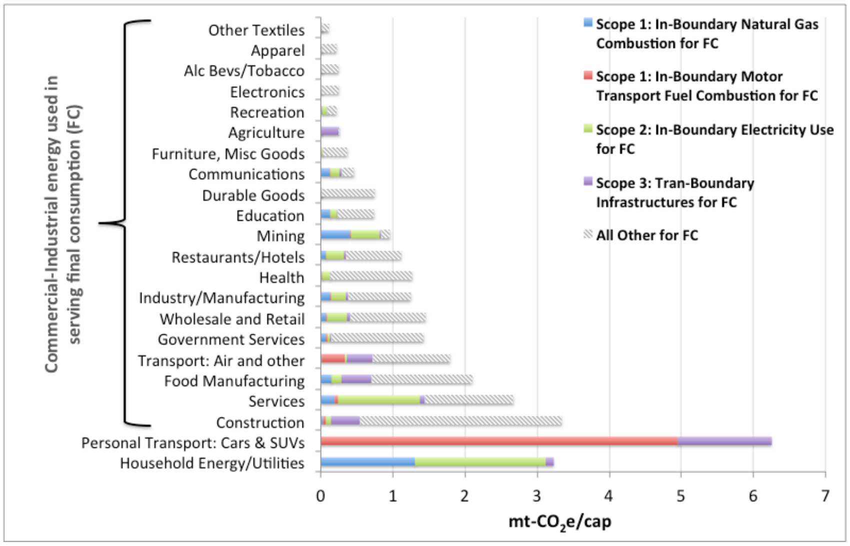


Figure 3-6: Denver – Illustrating GHG^{CBF} along with GHGs by Scopes in serving final consumption.

Lastly, Figure 3-7 illustrates GHG^{CBF} for Sarasota (net-consumer) by consumption category. GHGs shown are a result from serving Sarasota's final consumption, only. For Sarasota we compute that Scopes 1+2+3 serving final consumption equal 20 mt-CO$_2$e/cap (or 70% of CBF).

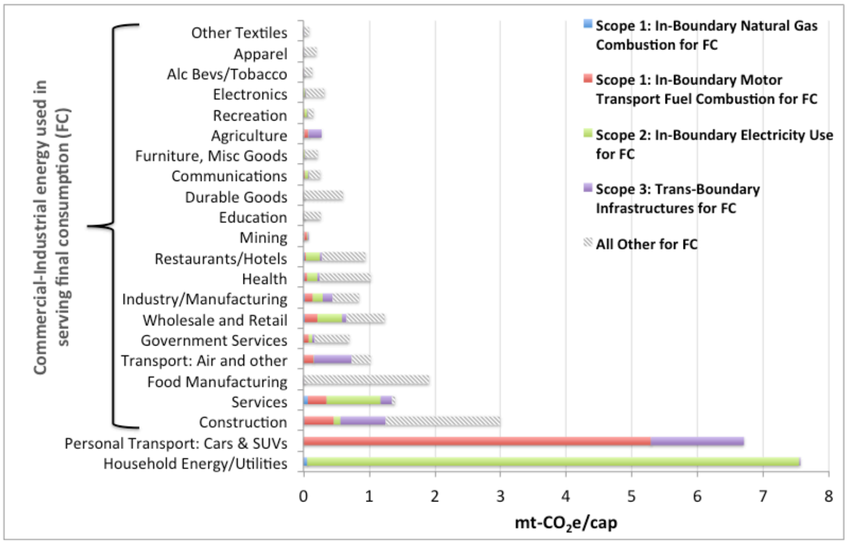


Figure 3-7: Sarasota – Illustrating GHG^{CBF} along with GHGs by Scopes in serving final consumption.

The perspective shown in Figure 3-5 thru Figure 3-7 reinforces some of the notable differences among community types. For example, lower activity in support of exports, and larger amounts of local energy used towards final consumption is highlighted in net-consumer Sarasota.

3.8 Conclusion

This preliminary case study of 3 cities suggests using caution in applying downscaled IO data to the city-scale because current IO downscaling methods do not incorporate energy-materials mapping/verification capabilities that are essential to show the percent local consumption that is being met by local production.

Analysis of the IO tables, however, provided a useful side-by-side theoretical comparison of territorial, TBIF and CBF GHG emission footprints for three types of communities: for a net-producing community (Routt), large metro community (Denver), and net-consuming community (Sarasota). Along with the mathematical relationships Equations 3-5, the data analysis reinforces and offers the following insights:

- No one method provides a larger or “more holistic” account of GHG emissions associated with communities.
- For high net-producing communities, which are net exporters of embodied GHG in trade after evening their supply-chains of basic infrastructures, TBIF will yield a larger GHG footprint compared to the CBF.
- For high net-consuming communities, TBIF will yield a lower GHG footprint compared to CBF.
- Most large metro areas are likely trade-balanced communities (after essential infrastructures are evened out), wherein TBIF and CBF would estimate similar GHG footprints. For such communities, given that there are errors and uncertainty in downscaling IO tables, for practical purposes, TBIF may provide a simplified approximation of CBF.

Understanding the nature of communities as highly producing, highly net consuming and net-Carbon trade balanced, after allocating out basic infrastructures, is essential for a more scientific understanding of their trans-boundary impacts.

Table 3-7: Differences between Unadjusted IMPLAN and Community GHG Inventory reports for three US communities.

		Electricity Use		**% community-wide electricity use that is generated locally**	
		Unadjusted IMPLAN[1]	Community GHG Inventory *[state benchmark]*[2]	Unadjusted IMPLAN	EPA eGRID[3] *(generation)*
Routt	Residential Intensity	980 kWh/HH/mo	833 *[554]* kWh/HH/mo	98%	100%
	Total Commercial-Industrial Use	287 GWh	251 GWh		
Denver	Residential Intensity	1,284 kWh/HH/mo	546 *[768]* kWh/HH/mo	91%	19%
	Total Commercial-Industrial Use	11,313 GWh	5,038 GWh		
Sarasota	Residential Intensity	952 kWh/HH/mo	1,403 *[1,367]* kWh/HH/mo	43%	0%
	Total Commercial-Industrial Use	1,730 GWh	1,861 GWh		

1. Unadjusted IMPLAN data was retrieved from each of communities input-output data file, provided by MIG, Inc.
2. Each of the three communities GHG Inventory Report as used to extract geographic energy use.
3. Local electricity generation retrieved from EPA eGRID (EPA, 2011).

4. Analysis of 21 US Cities and Implications for Metrics

4.1 Introduction

In the previous chapter mathematical relationships were derived and used to estimate city GHG emissions using three methods: Territorial, Trans-Boundary Infrastructure Footprint (TBIF), and Consumption-Based Footprint (CBF), each with a unique treatment of trans-boundary GHG emissions. While "Territorial" strictly measures GHGs from sources within the city boundary (in the territory), TBIF also accounts for the GHGs embodied in net-imports of infrastructures. CBF goes further to account for GHGs embodied in net-imports of non-infrastructures. Ramaswami et al. (2008) have articulated that TBIF is akin to production-based GHG accounting with key infrastructures that are hypothesized to be essential for economic production, allocated across cities based on their "use". Thus the metric for comparing cities using TBIF is expected to be GHG/GDP.

These key infrastructures (water, energy, food, transportation) have previously been hypothesized as being basic services supporting every city (Hillman & Ramaswami, 2010; Ramaswami, et al., 2008). Their use in residential-commercial-industrial sectors in a city is added to territorial as Scope 2 (electricity), or Scope 3 (other essential infrastructures), while surpluses being exported are subtracted. The allocations of these infrastructures were based on use, and on practical knowledge; this chapter explores the rationale for this approach, using meta-data for 21 cities.

The allocation of infrastructures (presented in chapter 3) yielded a 3-way typology of cities based on the GHGs embodied in net-imports of non-infrastructures. Where the net-imports of non-infrastructures are large, then the city is said to be net-consuming, but if the city is a large net-exporter (or large negative in net-imports) of non-infrastructures, then it is said to be a net-producer. The relative size of non-infrastructure net-imports are compared to TBIF, and if within +/- 15% the city is GHG trade balanced, >15% net-consumer, and <-15% net-producer. But why is a typology for cities important?

Beyond classifying cities, a typology for cities is important to understand the size of the trans-boundary supply-chains serving cities, enabling insight into the environmental impacts beyond the boundaries stimulated by in-city activities. The nature (i.e., what is the make-up of the supply-chain) along with size of the supply-chains are important to better understand GHG emissions associated with cities. For instance, chapter 3 showed that a net-producer has lower embodied GHGs in their supply-chains (imports) relative to in-boundary GHG. This is in contrast to a net-consumer city that has small in-boundary GHG relative to that embodied in imports. For the trade-balanced city, the GHG embodied in imports and exports (after allocating infrastructures) is about equal. But do these patterns hold for most cities within typologies? This chapter explores the nature and size of trans-boundary supply-chains for 21 US cities classifying them by typology. Additionally, other factors that shape typology, such as city population, and economy, will be explored to enhance our understanding of city types.

We also explore suitable metrics for comparing cities, and GHG emissions associated with them. The common metric presenting a city's GHGs has largely been per capita. Hillman & Ramaswami (2010) have indicated that GHGs per capita (i.e., GHG/resident) is not appropriate as seen in many studies. Cities with minimal commercial-industrial activities will artificially appear more efficient, while highly producing cities with larger amounts of industries will appear as less efficient (e.g., see Fig 3 in Hillman & Ramaswami). Ramaswami et al. (2011) propose GHG/GDP or GHG/job is appropriate for TBIF, while GHG/cap is suited for CBF. The availability for the first time of robust data for 21 cities can help identify best metrics to compare cities by.

Each of the above core topics are explored through a meta-analysis of 21 US cities. The cities are technically defined as US counties (Census, 2012a), but are called cities in short hand. The specific objectives of this chapter are:

1. Examine and articulate a rationale for allocating specific infrastructures based on "use" in a city's residential-commercial-industrial sectors.
2. Evaluate relationships between city typology (net-producers, net-consumers, and balanced) and city population size along with other proxies, to explore if larger cities tend to be balanced.

3. Compute the size of trans-boundary supply-chain footprints serving cities, by typology, relative to in-boundary GHGs.
4. Explore suitable metrics for comparing GHG emissions associated with cities that appropriately reflect urban efficiency characteristics.

We first discuss the meta-study dataset after which methods and results , addressing each of the objectives are presented as: a) Infrastructure rationale, b) Typology, c) Trans-Boundary Supply-Chains, and d) Metrics.

4.2 Case Cities and Data

4.2.1 Initial Dataset

A dataset on 55 cities was provided by ICLEI representing all ICLEI members that had completed GHG inventories by 2010. The cities in the dataset needed to be designated as counties for which Input-Output (IO) tables could be obtained. The dataset was first audited for cities that were not counties, of which 13 were identified, reducing the list to 42. Immediate local energy data required for the meta-analysis were residential-commercial-industrial building energy use, and motorized transportation energy use (gasoline/diesel), for which was unattainable for 5 cities, thus reducing the list to 37 cities. Lastly, 16 counties did not assign a representative to assist in acquiring local knowledge, required for contextual understanding of IO data. The dataset was reduced to 21 cities, all of which energy use data was benchmarked with comparable state data (see Supplemental Information (SI) in back of chapter).

Table 4-1: Cities from original 55 eliminated from meta-analysis.

City/County		Reason for not including
New Haven, CT	Missoula, MT	Urban classification: City rather than County
Blaine County, ID	Providence, RI	
Rock Island, IL	Franklin, TN	
New Orleans, LA	Dallas, TX	
Nantucket, MA	Richmond, VA	
Worcester, MA	Spokane, WA	
Baltimore, MD		
Sonoma County, CA	Alachua County, FL	Missing Data: Building energy use, or Transportation
Marin County, CA	Leon County, FL	
Alameda County, CA		
Fairbanks North Star, AK	Chatham County, NC	No county representative for local knowledge
San Luis Obispo, CA	Orange County, NC	
Los Angeles County, CA	Clackamas County, OR	
San Mateo County, CA	Montgomery County, PA	
La Plata County, CO	Williamson County, TX	
Montgomery County, MD	Albemarle County, VA	
Queen Anne's County, MD	Skagit County, WA	
Hennepin County, MN	Whatcom County, WA	

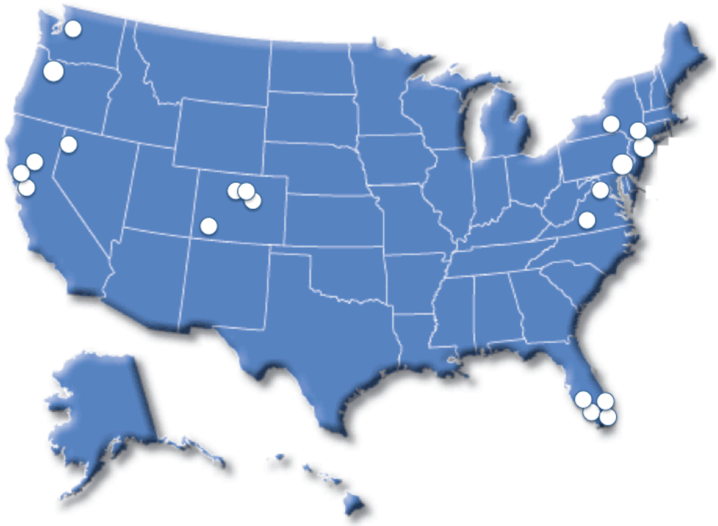


Figure 4-1: Map of 21 US cities in this meta-analysis

Table 4-2: Demographic & economic statistics for the 21 US cities in this meta-analysis.

County/Region	Population [a]	Population Density (people/sq-mile) [a]	GDP (mill $) [b]	Jobs [a]
NYC, NY	8,363,710	27,012	$658,701	3,679,345
DVRPC, PA/NJ	5,499,482	1,477	$300,985	2,548,018
Miami-Dade, FL	2,387,170	1,240	$109,939	998,241
Broward, FL	1,759,591	1,449	$74,702	751,629
Oregon METRO, OR	1,600,751	517	$84,866	831,966
Philadelphia, PA	1,448,394	11,254	$70,474	632,755
Sacramento, CA	1,374,724	1,403	$63,517	624,259
Westchester, NY	949,355	2,190	$57,012	411,005
Multnomah, OR	714,567	1,637	$47,457	449,358
Snohomish, WA	669,887	318	$21,656	221,050
Denver, CO	588,349	3,774	$62,817	442,739
Washoe, NV	410,443	64	$19,949	208,318
Sarasota, FL	369,535	635	$7,927	158,001
Collier, FL	315,839	155	$13,682	131,937
Boulder, CO	282,304	386	$17,719	154,367
Loudoun, VA	278,797	534	$15,903	129,253
Napa, CA	133,522	172	$6,940	65,201
Tompkins, NY	101,136	212	$4,116	50,689
Roanoke, VA	90,420	359	$2,946	35,830
Broomfield, CO	53,691	1,951	$3,927	30,517
Routt, CO	21,580	9	$1,474	14,245

a. Retrieved from US Census (Census, 2011)
b. Retrieved from IMPLAN (IMPLAN, 2010)

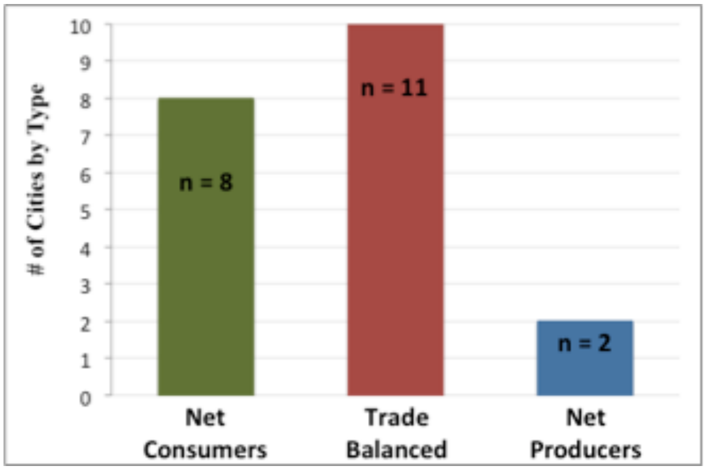


Figure 4-2: Number of cities by type in meta-analysis.

4.2.2 City Characteristics

City Characteristics from 21 US Cities: Table 4-2 lists the 21 US cities of this analysis, along with a few parameters that elucidate the uniqueness' of these cities. Population is as large as 8 million (NYC) and as small as 21,000 (Routt). Population density ranges as high as 27,000 people/square-mile, to as low as 9 people/square-mile. These two parameters, among others, affect energy use and GHGs in cities. To show some of the differences in in-boundary energy use across these cities, we compute energy use efficiencies for commercial-industrial, residential, and transportation sectors for the 21 cities. The computed efficiencies are:

Commercial-Industrial: kWh/GDP; therms/GDP; kBTU/GDP (all on annual basis)

Residential: kWh/cap/mo; therms/cap/mo; kBTU/cap/mo

Motorized Surface Transport: VMT/(residents+jobs)/day

Table 4-3 shows a summary of the most efficient, and the most inefficient cities from the sample of 21 cities, by parameter. We note the large range in cities by parameter. In terms of commercial-industrial energy use, NYC is the most efficient (349,235 kBTU/GDP/yr), and Roanoke is the most inefficient (1,214,728 kBTU/GDP/yr). In terms of residential energy use, Broward is the most efficient (1,788 kBTU/cap/mo), and Roanoke is the most inefficient (4,093 kBTU/cap/mo). Finally, in terms of transportation system efficiency, NYC is the most efficient (5.8 VMT/(res+job)/day), and Sarasota is the most inefficient (24.3 VMT/(res+job)/day).

Table 4-3: Summary of most efficient, and most inefficient cities by energy use efficiency parameter.

	Most Efficient	Most Inefficient
Commercial-Industrial: [kBTU/GDP/yr]; {city}	[29,103]; {NYC}	[101,227]; {Roanoke}
Residential: [kBTU/cap/mo]; {city}	[1,788]; {Broward}	[4,093]; {Roanoke}
Transportation: [VMT/(res+job)/day]; {city}	[5.8]; {NYC}	[24.3]; (Sarasota)

The following sets of figures (Figure 4-3 thru Figure 4-9) show how the 21 cities compare to the US average for each of the energy efficiency parameters. These figures show that although the sample of cities is small, and represents all city-counties that had worked with ICLEI as of 2010, the cities' energy efficiency characteristics are widely distributed across the national averages.

Commercial-Industrial Energy Efficiencies:

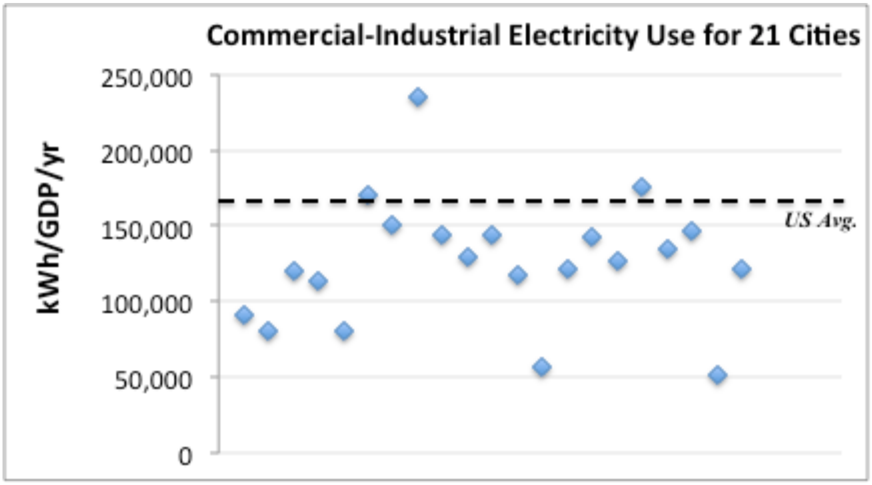


Figure 4-3: Commercial-Industrial electricity use for 21 cities distributed across the US average.

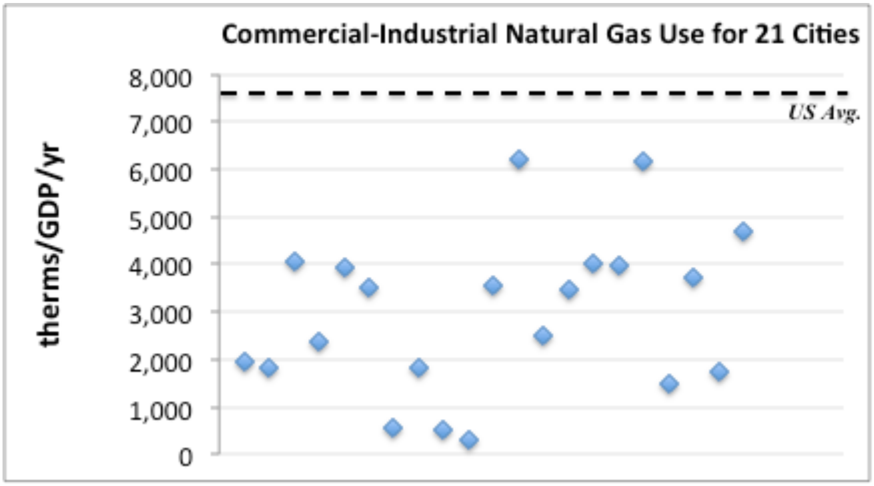


Figure 4-4: Commercial-Industrial natural gas use for 21 cities distributed across the US average.

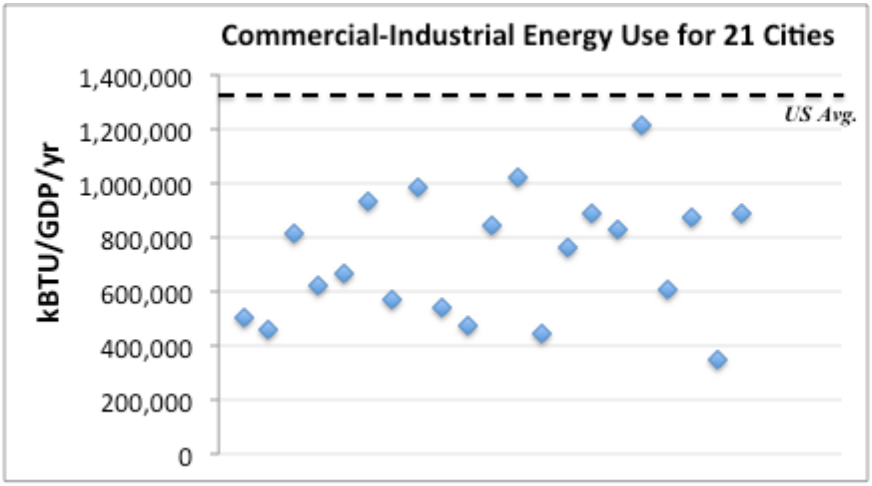


Figure 4-5: Commercial-Industrial energy use for 21 cities distributed across the US average.

Residential Energy Efficiencies:

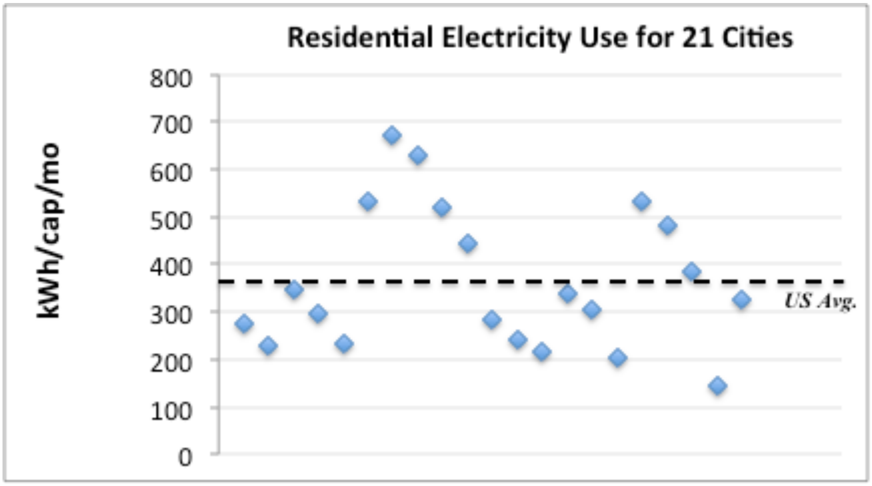


Figure 4-6: Residential electricity use for 21 cities distributed across the US average.

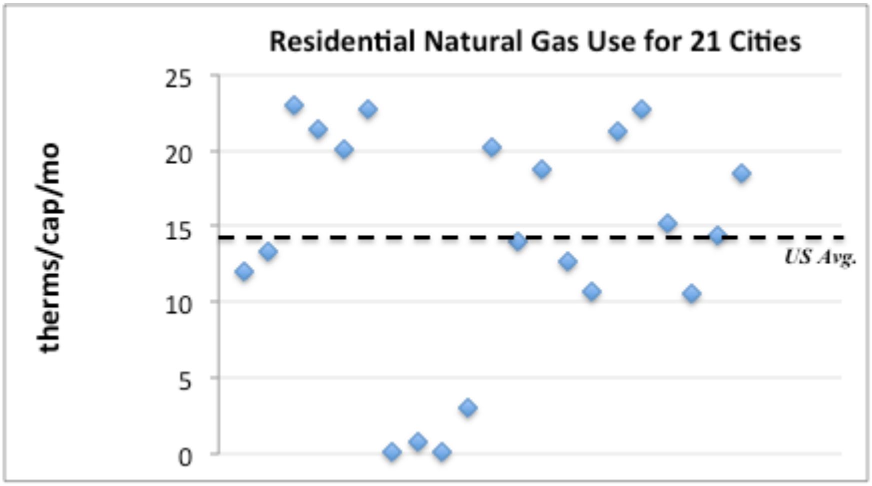


Figure 4-7: Residential natural gas use for 21 cities distributed across the US average.

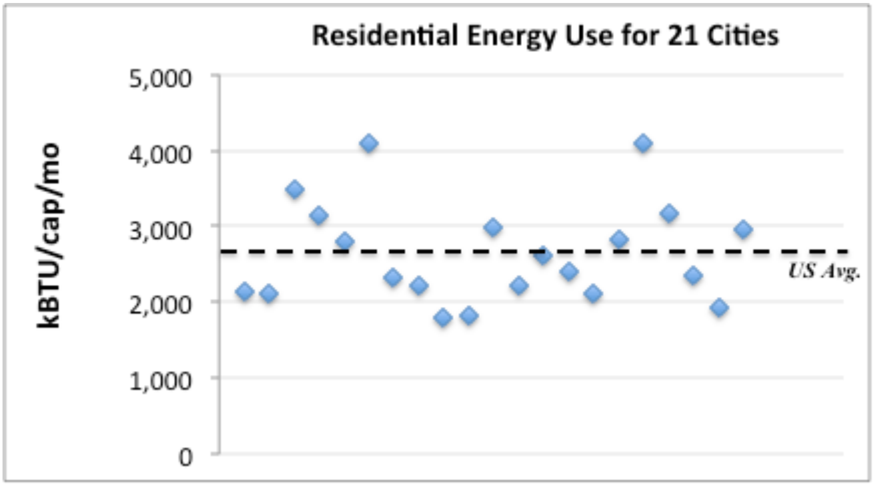


Figure 4-8: Residential energy use for 21 cities distributed across the US average.

Transportation System Efficiency:

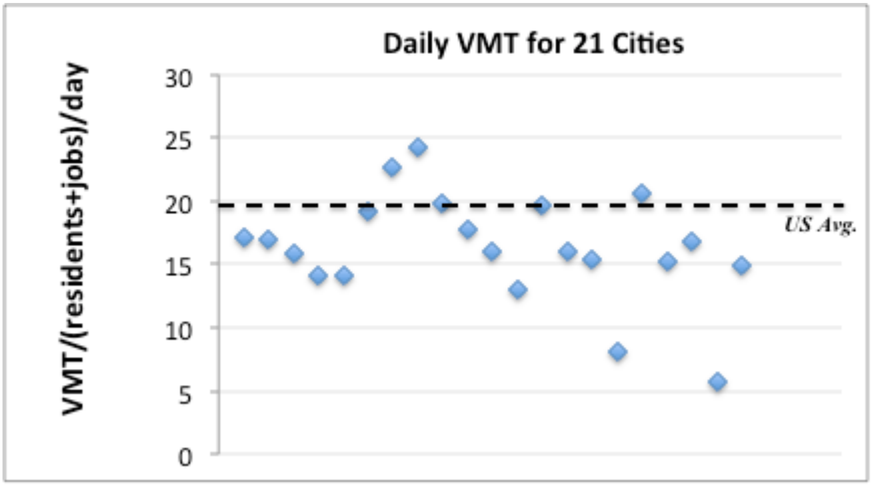


Figure 4-9: Transportation system efficiency for 21 cities distributed across the US average.

4.2.3 IO Table Data

IO tables for the 21 cities were obtained from MIG IMPLAN, Inc. Because IO tables are not originally intended to be used for tracking energy use and GHGs, energy flows emerging from IO tables must be compared to actual energy end use data and corrected for any mismatches. Mismatches in IO tables between monetary flows and energy flows commonly stem from three reasons: 1) residential energy use is downscaled from national data without consideration for local wealth, climate, or urban form; 2) self-employed residents of the city owning and operating energy assets outside of the city; and 3) large corporate headquarters located in the city. Both 2) and 3) present the illusion of highly producing sectors. Thus, mismatches when compared to actual energy end use reported by cities must be corrected where identified. Energy end use data from each of the 21 cities provided by ICLEI allowed calibration for electricity, natural gas, along with gasoline and diesel use within the community. As shown in chapter 3, there were differences in IMPLAN projection of local electricity generation compared to EPA eGRID, thus eGRID was used to adjust for the community-wide electricity use that is generated in the city (EPA, 2011). Procedures for comparing energy flows, and calibrating IO tables are described in section 3.4 (chapter 3). The comparisons between the unadjusted IO table and GHG inventory reports are presented in Appendix A for each fuel across the 21 cities.

Sector Output/Trade was analyzed done to evaluate the top exporting sectors, by dollar output, for each city. This step was key towards identifying artificially high producing sectors caused by self-employed residents or by large headquarters. In the absence of consistent, more robust databases, an attempt to validate the top sectors was approached through the use of publicly available data. Seen in Table 4-4 are the top three trade sectors for the 21 cities. Upon review, a few of these make rational sense: Snohomish (Aircraft) supporting operations for Boeing; NYC (Investment services) is a financial hub; and Napa (Wineries) a large producer of wine. Others required additional research to confirm, such as: Loudoun (Telecommunications) was verified through a series of local reports (TAG, 2002); and Routt (Coal Mining) was also found to have large coal mining operations (Valley, 2011). Meanwhile, those that were found not to agree with the physical case were zeroed out, as they translate to large GHG emissions.

Table 4-4: Top three output trade sectors for 21 US cities.

City *(Type)*	Description	% of Total	Total Exports (mill $)
Collier *(C)*	Real estate related services	15%	$7,959
	Hotels and motel services	4%	
	Amusements and recreation	4%	
Sarasota *(C)*	Professional and technical	10%	$6,106
	Metal window and door manufacturing	8%	
	Real estate	8%	
Snohomish *(C)*	Aircraft manufacturing	50%	$18,846
	Aircraft parts and equipment	4%	
	Telecommunications	4%	
Sacramento *(C)*	Real estate	12%	$25,675
	Telecommunications	9%	
	Hospitals	7%	
Broward *(C)*	Wholesale trade distribution services	10%	$58,116
	Real estate related services	9%	
	Rental services	3%	
Boulder *(C)*	Software publishers	13%	$13,162
	Scientific research and development services	7%	
	Pharmaceutical and medicine manufacturing	7%	
Roanoke *(C)*	Insurance	16%	$2,990
	Computer related services	9%	
	Motor homes	6%	
Westchester *(C)*	Management of companies and enterprises	10%	$32,314
	Real estate	9%	
	Telecommunications	7%	
Loudoun *(B)*	Telecommunications	40%	$12,115
	Air transportation services	8%	
	Computer systems design services	4%	
Napa *(B)*	Wineries	47%	$5,915
	Pharmaceutical and medicine manufacturing	8%	
	Real estate	5%	
DVRPC *(B)*	Refined petroleum products	7%	$154,658
	Pharmaceutical preparations	6%	
	Wholesale trade distribution services	4%	
NYC *(B)*	Securities, commodity, investments services	24%	$409,030
	Advertising and related services	8%	
	Real estate related services	7%	
Philadelphia *(B)*	Funds- trusts- and other financial vehicles	10%	$46,284
	Hospitals	9%	
	Colleges- universities- and junior colleges	9%	
Denver *(B)*	Oil and natural gas	12%	$48,761
	Real estate related services	11%	
	Air transportation services	6%	
Washoe *(B)*	Funds, trusts, and other financial services	10%	$16,568
	Hotels and motel services	8%	
	Miscellaneous manufactured products	5%	
METRO *(B)*	Semiconductor and related devices	12%	$51,060
	Wholesale trade distribution services	10%	
	Management of companies and enterprises	3%	
Broomfield *(B)*	Telecommunications	16%	$6,563
	Management of companies and enterprises	7%	
	Pharmaceutical preparations	6%	
Multnomah *(B)*	Wholesale trade distribution services	6%	$47,769
	Management of companies and enterprises	5%	
	Insurance	3%	
Miami-Dade *(B)*	Wholesale trade distribution services	12%	$58,535
	Water transportation services	9%	
	Air transportation services	6%	
Routt *(P)*	Real estate	19%	$1,051
	Coal mining	16%	
	Amusements and recreation	9%	
Tompkins *(P)*	Junior colleges, colleges, universities	40%	$4,046
	Motor vehicle parts	11%	
	Aircraft engines and engine parts	4%	

IO data is also verified against two econometric parameters that are generally publicly available for US cities; GDP/capita and Income/cap. GDP/cap is reported by the BEA – nationally, for states, and for metropolitan statistical areas (MSA) (BEA, 2012). We obtain city specific GDP/cap from IMPLAN, and compare to the GDP/cap for the corresponding MSA retrieved from BEA. Meanwhile, BEA does publish estimates for per capita income down to the county scale, thus allowing for a direct comparison to the same retrieved from IMPLAN. Table 4-5 shows these comparisons across the 21 cities in this analysis. *Note, MSA's for each of the 21 cities are shown in S4-4.*

Results from Income/cap between the two datasets (IMPLAN & BEA) show both are generally in-line with each other since both report county-level data; however, there are some apparent differences in GDP/cap between the two.

In our IMPLAN model NYC is represented by the five county region of Bronx, Kings, New York, Queens, and Richmond counties, constituting a population of 8.4 million, while the comparative MSA is the New York-Northern New Jersey-Long Island NY-NJ-PA MSA which has a total population of 18.9 million (Census, 2011). NYC (five counties) may be both a larger consumer and producer (exporter) of goods/services when compared to its average MSA, potentially explaining NYC's larger GDP/cap compared to its MSA. Another notable difference in GDP/cap is seen in Denver, where IMPLAN estimates yield $106,769 GDP/cap and BEA MSA average is $57,595 GDP/cap. The Denver-Aurora-Broomfield MSA consists of ten counties (Denver, Arapahoe, Jefferson, Adams, Douglas, Broomfield, Elbert, Park, Clear Creek, and Gilpin) with a total population of 2.5 million (Census, 2011). As shown in Table 4-6, GDP/cap for the total Denver-Aurora-Broomfield MSA as estimated from IMPLAN is in-line with the estimate obtained from BEA. Therefore we conclude that some of the differences setting Denver (county) apart from some of the other counties is the MSA can be higher employee compensation, and/or higher final consumption and exports.

Table 4-5: Per capita GDP and Incomes from IMPLAN and BEA, for 21 US cities.

	GDP/cap		Income/cap	
County	**IMPLAN**	**BEA (MSA avg)**	**IMPLAN**	**BEA (county)**
NYC, NY	$78,757	$60,965	$51,814	$50,881
DVRPC, PA/NJ	$54,730	$50,563	$46,149	$40,914
Miami-Dade, FL	$46,054	$43,826	$35,852	$32,057
Broward, FL	$42,454	$45,847	$42,276	$42,673
Oregon METRO, OR	$53,017	$52,122	$40,402	$39,826
Philadelphia, PA	$48,657	$51,225	$32,996	$31,288
Sacramento, CA	$46,203	$43,489	$35,473	$35,110
Westchester, NY	$60,053	$57,879	$64,859	$63,826
Multnomah, OR	$66,414	$56,099	$41,913	$41,619
Snohomish, WA	$32,328	$58,332	$36,416	$34,960
Denver, CO	$106,769	$57,595	$52,017	$51,895
Washoe, NV	$48,603	$46,095	$44,888	$44,356
Sarasota, FL	$21,450	$34,701	$48,812	$50,033
Collier, FL	$43,319	$43,216	$60,001	$63,620
Boulder, CO	$62,764	$55,486	$47,624	$46,376
Loudoun, VA	$57,042	$67,743	$44,420	$50,009
Napa, CA	$51,980	$49,291	$45,519	$45,677
Tompkins, NY	$40,698	$33,947	$33,200	$33,902
Roanoke, VA	$32,584	$39,643	$41,358	$38,240
Broomfield, CO	$73,144	$57,595	$34,788	$38,215
Routt, CO	$68,322	$46,938	$43,723	$46,021

Table 4-6: per capita GDP and Income for the 10 counties of the Denver-Aurora-Broomfield MSA.

County	Population	Jobs	GDP (mill $)	Income (mill $)	GDP/cap	Income/cap
Denver	588,349	646,259	$62,817	$30,604	$106,769	$52,017
Broomfield	53,691	35,618	$3,927	$1,868	$73,144	$34,788
Arapahoe	545,089	423,494	$44,442	$27,105	$81,531	$49,725
Jefferson	529,354	289,807	$22,757	$25,159	$42,991	$47,527
Adams	422,495	202,704	$14,429	$12,598	$34,151	$29,818
Douglas	272,117	110,158	$9,935	$14,418	$36,509	$52,986
Elbert	22,720	6,245	$339	$871	$14,940	$38,353
Park	17,004	3,830	$200	$502	$11,751	$29,502
Clear Creek	8,956	5,198	$420	$520	$46,884	$58,049
Gilpin	5,091	5,271	$431	$186	$84,674	$36,534
Denver-Aurora-Broomfield MSA TOTAL	**2,464,866**	**1,728,584**	**$159,697**	**$113,830**	**$64,789**	**$46,181**

<u>The modified IMPLAN model</u> was used to analyze in-boundary and trans-boundary GHGs after correcting for energy end-use obtained from the ICLEI database and electricity generation from eGRID. Upon also examining the Toxic Release Inventory (TRI) (EPA, 2012), and the County Business Patterns (Census, 2012b), we discovered that cities appear to have good energy “use” data, but do not report GHGs from industrial process (non-fossil combustion) activities, since cities are not required to do so. Table 4-7 shows some of the in-boundary industrial process activities identified through TRI for selected cities that are not reported by cities. Therefore, we proceed with the analysis in this chapter using the modified IMPLAN IO tables, corrected for key parameters, as a model to represent the various city types. We do not assert that the IMPLAN models represent each individual city accurately, but we expect different city types to be well represented with reasonable in-boundary energy use and associated trans-boundary supply-chains.

Table 4-7: Examples of industrial processes located in selected US cities.

City	In-Boundary Industrial Processes
Boulder	Asphalt paving, Cement Production, Heavy Industrial Equipment, Computer Parts
Broward	Asphalt, Concrete Bricks, Stone
Miami-Dade	Petroleum Refining, Cement Production, Chemical Production
Napa	Crop Production for wine industry
Oregon METRO	Petroleum Refining, Cement Production, Chemical Production
Philadelphia	Petroleum Refining
Routt	Coal Mining
Sacramento	Chemicals, Asphalt, Brick/Tile

4.3 Methods and Results

4.3.1 Rationale for Infrastructure Allocation

In this section we develop a rationale for proposing infrastructures that should be allocated to cities based on use. In developing a rationale, two plots for each infrastructure sector were compiled to evaluate the relationships between GDP and GHGs across the 21 cities. The first plot in each series shows GDP vs. GHGs from Infrastructure Use (local plus imports), and the second plot shows GDP vs. GHGs embodied in exports, for each respective infrastructure sector. Note, infrastructures relate to Water, Sanitation, Energy, Food, Transportation, and Materials for Shelter. The following criteria were proposed to evaluate which sectors may be considered infrastructures:

a. High correlation between community GDP vs. GHG in community-wide (residential-commercial-industrial) use of a sector (R^2>0.70), and
b. Weak correlation between community GDP vs. GHG embodied in exports of that same sector (R^2<0.30)

This combination is considered to represent a strong correlation of infrastructure provisioning on economic development, while also illustrating that exports of these sectors do not significantly contribute to economic development broadly across cities. In other words, if a strong correlation (R^2 > 0.70) between GDP and GHGs from

Infrastructure use is observed, it suggests that the respective infrastructure sector is important for economic activity. However, if the exports of the same show a weak correlation ($R^2 < 0.30$) with GDP across the 21 cities, it suggests the sector in question is likely not a significant creator of GDP across the board.

The identical approach is also extended to all other (non-infrastructures) goods and services allowing for an evaluation of additional supply-chains that may be largely considered as basic for any economy.

We present Table 4-8, which shows the percent GHGs that each of the forthcoming sectors contribute to national U.S. GHGs. It's noted that the infrastructure sectors alone cover 63% of national GHGs. The last two columns of the table show the computed regression fits (correlations) for each pair (Use and Exports) for the 21 cities; maintaining US average emission factors for comparison. Let us begin with electricity.

Most electricity used in cities is generated outside of cities. In our sample of 21 cities, three (or 14%) produce surplus electricity for export. Figure 4-10 shows a strong correlation between GDP and GHGs in community-wide electricity use ($R^2 = 0.84$), while GDP vs. GHGs embodied in electricity exports ($R^2 = 0.02$) confirms that not many communities are producers of surplus electricity. Indeed this may effectively provide a rationale for considering electricity as a Scope 2 item.

Table 4-8: Regression correlations (R^2) from Use and Export from all sectors for 21 cities, along with the % contributing to national (U.S.) GHGs.

	Sector Category	% of National GHGs	R^2 from Use	R^2 from Export
Current Infrastructure Sectors	Electricity	39.7%	0.84	0.02
	Food Agriculture/Livestock	7.4%	0.73	0.14
	Water/WW	4.3%	0.30	0.14
	Freight	3.4%	0.46	0.41
	Fuel Production	3.1%	0.82	0.13
	Air Travel	2.8%	0.70	0.43
	Cement	1.6%	0.73	0.12
	Iron/Steel	3.3%	0.77	0.13
Potential Infrastructure Sectors	Transport Services (Marine, Rail)	4.5%	0.84	0.38
	Mining	3.9%	0.79	0.007
	Durable Goods	0.3%	0.87	0.04
	Communications	0.5%	0.75	0.27
	Alcoholic Beverages, Tobacco	0.1%	0.77	0.01
	Natural Gas Production	0.5%	0.19	0.03
Other Sectors	Industry/Manufacturing	8.9%	0.93	0.51
	Services	4.3%	0.59	0.67
	Government Services	4.0%	0.41	0.31
	Construction	3.3%	0.34	0.35
	Wholesale/Retail	1.0%	0.27	0.65
	Food Manufacturing	0.9%	0.93	0.51
	Education	0.6%	0.24	0.03
	Restaurant/Hotels	0.5%	0.63	0.48
	Electronics	0.4%	0.36	0.19
	Health	0.3%	0.34	0.28
	Recreation	0.2%	0.49	0.10
	Other Textiles	0.1%	0.87	0.79
	Furniture	0.1%	0.89	0.55
	Apparel	0.02%	0.94	0.68

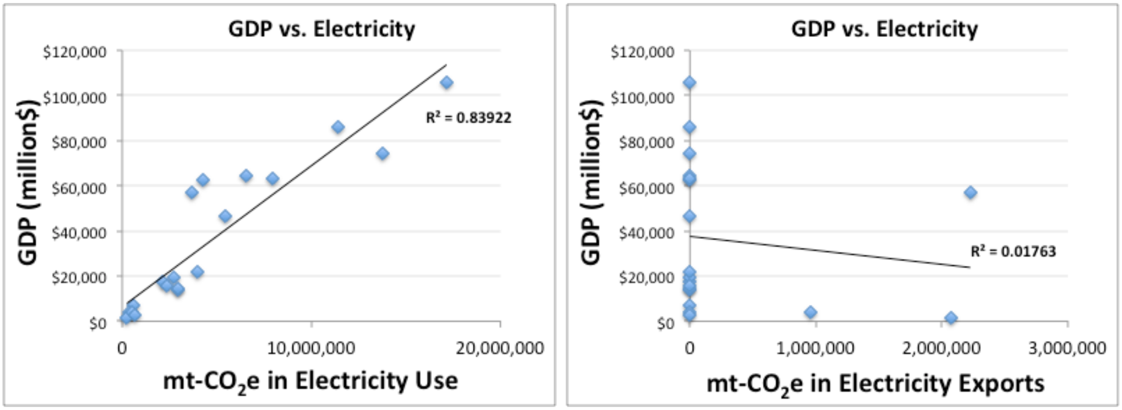


Figure 4-10: Electricity - GDP vs. GHGs from Use (left) and Export (right).

As shown in Figure 4-11, Food Agriculture/Livestock also meets the criterion with high (R^2 = 0.73) correlation between community GDP and GHG in use, and weak correlation (R^2 = 0.14) between community GDP and GHG embodied in exports.

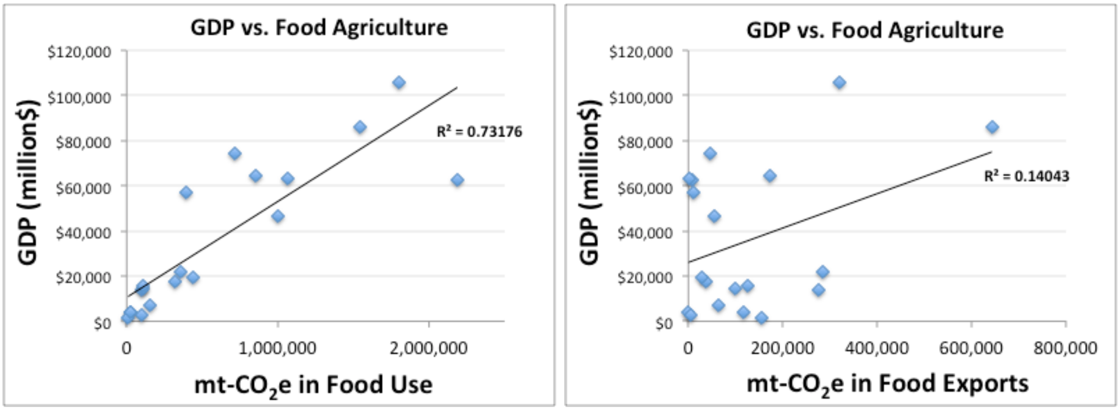


Figure 4-11: Food Agriculture - GDP vs. GHGs from Use (left) and Export (right).

The GHGs associated with Fuel Refining (Figure 4-12) shows similar patterns. The correlation between community GDP and GHG in use is high (R^2 = 0.82), and the correlation between community GDP and GHG embodied in exports is weak (R^2 = 0.11).

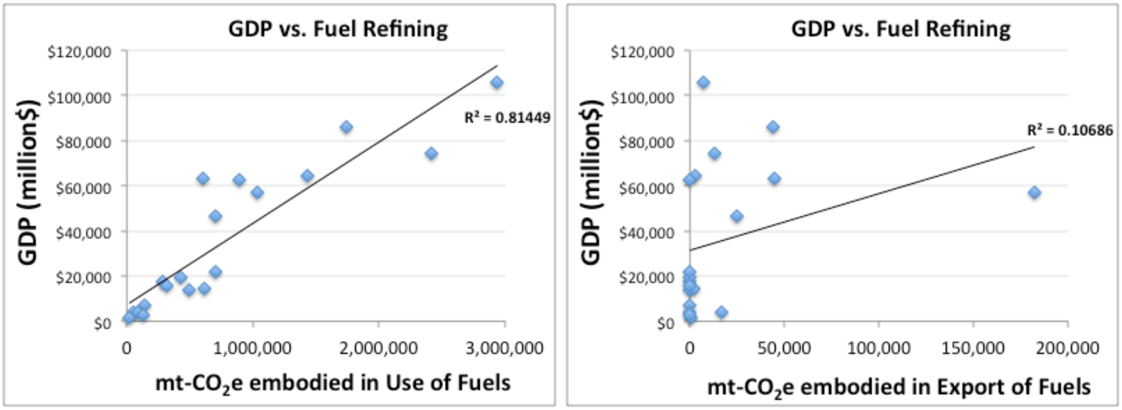


Figure 4-12: Fuel Refining - GDP vs. GHGs from Use (left) and Export (right).

The remaining infrastructure correlations are placed at the end of the chapter in SI (S 4-6, a-f). Note that the sample of 21 cities is relatively small, and with a larger set of cities more pronounced patterns might emerge. As for the non-infrastructure sectors (all of which are shown in SI: S 4-6, g-v), Services (Figure 4-13), and Health Care (Figure 4-14) are examples of sectors where both the Use and Export are correlated to economic development, hence unsuited to allocation. Meanwhile, further investigation reveals that Iron/Steel use is meets our criterion, and may be suited for allocation.

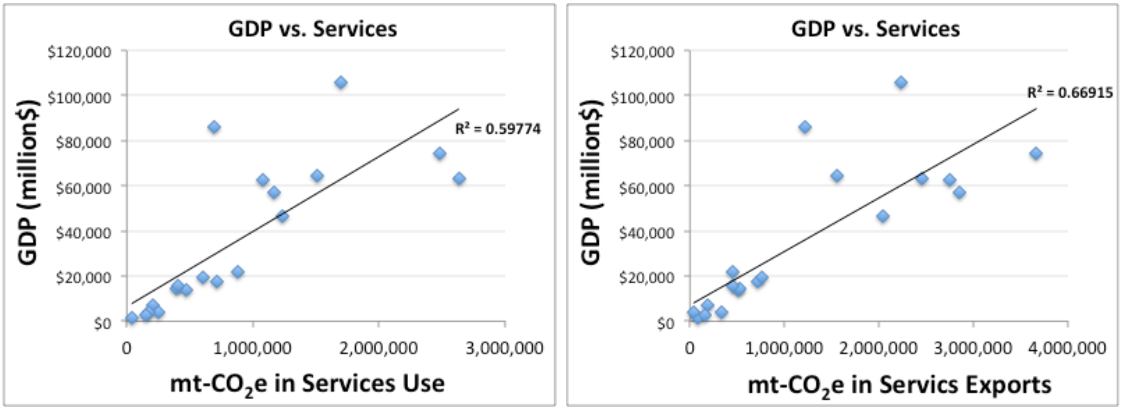


Figure 4-13: Services - GDP vs. GHGs from Use (left) and Export (right).

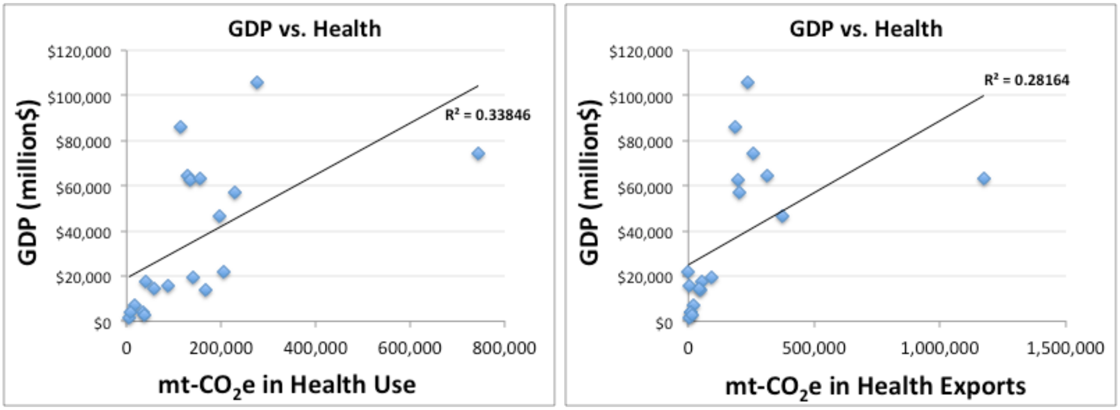


Figure 4-14: Health - GDP vs. GHGs from Use (left) and Export (right).

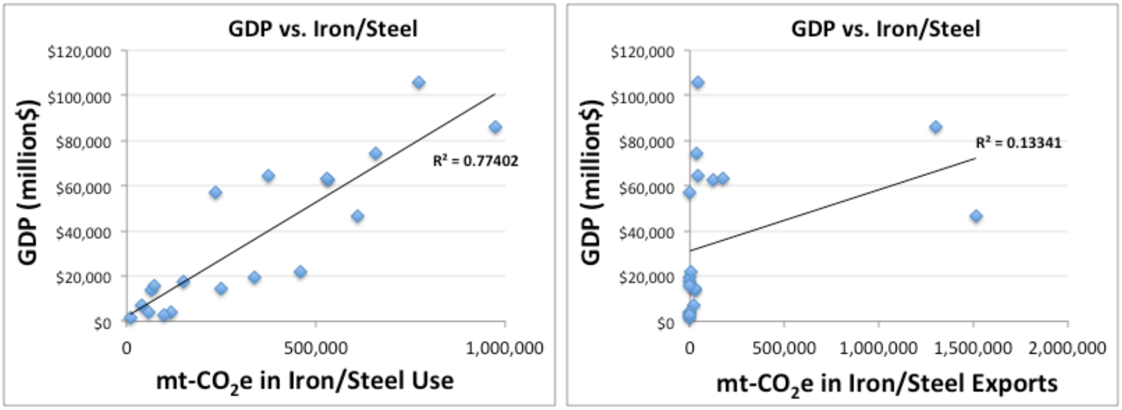


Figure 4-15: Iron/Steel - GDP vs. GHGs from Use (left) and Export (right).

Figure 4-15 shows that Iron/Steel indeed may be a common supply-chain serving all cities, and only one group, the Multnomah/Oregon METRO tandem, which are collocated in the same area, were computed as net-exporters of Iron/Steel. Therefore, Iron/Steel production was included as an infrastructure sector in the analysis that follows, given the large amounts of Iron/Steel in the built environment. Note, as this analysis uses IO tables to quantify the supply-chains of sectors, additional effort is required to identify public data sources that would allow cities to effectively allocate Iron/Steel.

4.3.2 City Typology, Relationships to Population, and Proxies

City Typology was covered in depth in chapter 3, and generates a 3-way typology for cities as: Net-Consumers, Net-Producers, or GHG Trade Balanced.

In a *trade-balanced* community, where $\mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}} << \mathrm{GHG}_{\mathrm{Scopes1+2+3}}^{\mathrm{TBIF}}$, $\mathrm{GHG}^{\mathrm{TBIF}} \approx \mathrm{GHG}^{\mathrm{CBF}}$.

In a *producer* community, where $\mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}}$ is a large negative, $\mathrm{GHG}^{\mathrm{TBIF}} > \mathrm{GHG}^{\mathrm{CBF}}$.

In a *consumer* community, where $\mathrm{GHG}_{\mathrm{M_{net}}}^{\mathrm{non-infra}}$ is a large positive, $\mathrm{GHG}^{\mathrm{TBIF}} < \mathrm{GHG}^{\mathrm{CBF}}$.

where $\mathrm{GHG}^{\mathrm{non-infra}}{}_{\mathrm{Mnet}}$ are the GHG embodied in net-imports of non-infrastructure sectors, and is compared to TBIF to determine its relative size. In practice, a community is said to be a Net-Consumer if $\mathrm{GHG}^{\mathrm{non-infra}}{}_{\mathrm{Mnet}}$ are >15% compared to TBIF; a Net-Producer if < -15% Net-Producer; and Trade Balanced if within +/- 15%. Note, we refer to the ratio of $\mathrm{GHG}^{\mathrm{non-infra}}{}_{\mathrm{Mnet}}$/TBIF as the typology degree. In our sample of sample of 21 cities, 8 are computed as Net-Consumers, 11 Trade Balanced, and 2 Net-Producers. Among them are 3 exporters of electricity (Routt, Tompkins, and Westchester), and 1 net-exporter of cement (Miami-Dade). Table 4-9 (net-producers), Table 4-10 (balanced), and Table 4-11 (net-consumers) present the typology degree for each city.

Results show that larger cities tend to be balanced, signaling a strong presence of both production and consumption activities in larger US cities. The other balanced communities appear in close proximity to large metros, possibly signaling links between their economies (e.g., Broomfield near Denver; Washoe near Reno; Loudoun near Washington DC).

Table 4-9: Degree by which communities are measured as Net-Producer, along with alternate metrics for representing typology.

Net-Producer Community	**$GHG^{non\text{-}infra}_{Mnet}/GHG^{TBIF}$**	**Comm-Ind kWh/cap**	**Energy Use Ratio (Comm-Ind/HH)**	**Employment Intensity (jobs/cap)**	**GDP/resident ($/cap)**
Tompkins, NY*	-22%	4,811	1.56	0.50	$40,698
Routt, CO *	-39%	13,271	2.06	0.66	$68,322

* net exporter of infrastructure

Table 4-10: Degree by which communities are measured as Trade Balanced, along with alternate metrics for representing typology.

Trade-Balanced Community	**$GHG^{non\text{-}infra}_{Mnet}/GHG^{TBIF}$**	**Comm-Ind kWh/cap**	**Energy Use Ratio (Comm-Ind/HH)**	**Employment Intensity (jobs/cap)**	**GDP/resident ($/cap)**
Loudoun, VA	15%	7,761	0.92	0.40	$57,042
Napa, CA	11%	4,333	0.94	0.49	$51,980
DVRPC, PA/NJ	10%	6,651	1.36	0.46	$54,730
NYC, NY	9%	4,084	1.19	0.44	$78,757
Philadelphia, PA	8%	5,900	1.19	0.44	$48,657
Denver, CO	6%	8,704	2.11	0.75	$106,769
Washoe, NV	2%	6,836	1.15	0.51	$48,603
METRO, OR	-3%	7,739	1.86	0.52	$53,017
Broomfield, CO	-11%	8,326	1.21	0.57	$73,144
Multnomah, OR	-13%	8,065	1.74	0.63	$66,414
Miami-Dade, FL*	-7%	5,925	1.00	0.42	$46,054

* net exporter of infrastructure

Table 4-11: Degree by which communities are measured as Net-Consumer, along with alternate metrics for representing typology.

Net-Consumer Community	**$GHG^{non\text{-}infra}_{Mnet}/GHG^{TBIF}$**	**Comm-Ind kWh/cap**	**Energy Use Ratio (Comm-Ind/HH)**	**Employment Intensity (jobs/cap)**	**GDP/resident ($/cap)**
Collier, FL	42%	6,568	0.88	0.42	$43,319
Sarasota, FL	34%	5,123	0.79	0.43	$21,450
Snohomish, WA	25%	4,798	0.99	0.33	$32,328
Sacramento, CA	25%	4,262	0.90	0.45	$46,203
Broward, FL	23%	6,132	1.07	0.43	$42,454
Boulder, CO	22%	7,475	1.23	0.55	$62,764
Roanoke, VA	20%	5,738	0.81	0.40	$32,584
Westchester, NY*	23%	3,464	0.86	0.43	$60,053

* net exporter of infrastructure

Next, cities were organized by type (see Table 4-9 thru Table 4-11), and the absolute value of the typology degree was plotted against population to explore patterns. Our initial hypothesis was that larger cities (based on population) would tend to be more trade balanced.

As seen in Figure 4-16, smaller communities (lower populations) can be any of the three typologies. However, a convergence towards trade balanced in GHG may be emerging for larger communities (>2,000,000 people). Therefore it may be that larger communities are consistently balanced, hosting both large amounts of production and consumption activities. Recall that the typology degree represents the % of GHG in non-infrastructure imports or exports relative to TBIF.

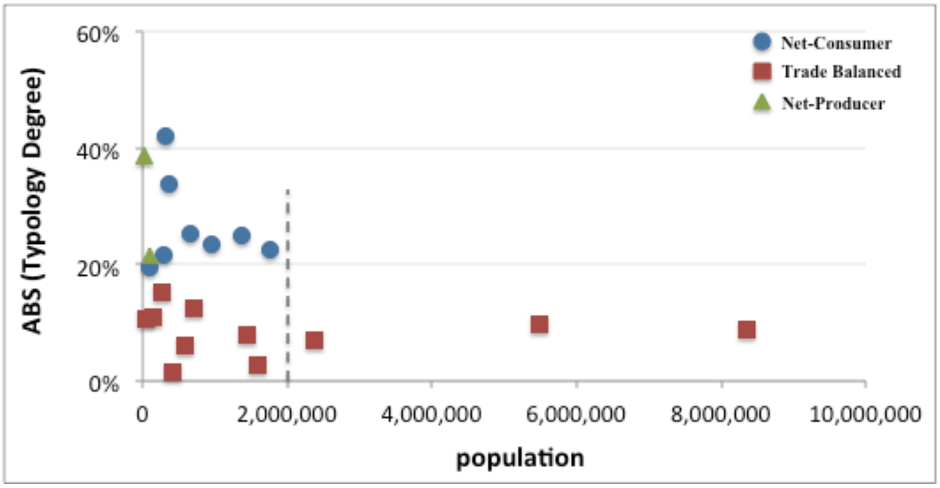


Figure 4-16: Absolute value of typology degree vs. population for 21 communities. Larger communities are shown to approach trade balanced.

We also explored various parameters that we hypothesized as being reasonable proxies for typology. The three parameters are: total commercial-industrial electricity use per capita *(Comm-Ind kWh/cap)*, ratio of commercial-industrial energy use (in kBTU) to residential energy use (in kBTU) *(Comm-Ind/HH)*, and employment intensity *(Jobs/cap)*. Note, the corresponding US averages for the three parameters are: Comm-Ind kWh/cap = 7,704 kWh/cap; Comm-Ind/Res = 1.99; Jobs/cap = 0.44. The three parameters are evaluated for correlation with our typology degree in Figure 4-17 thru Figure 4-19.

While each of the observed trends are as anticipated, the ratio between commercial-industrial energy use and residential energy use *(Comm-Ind/HH)*, appears the best (R^2 = 0.5) suited to serve as a quick proxy for identifying city typology.

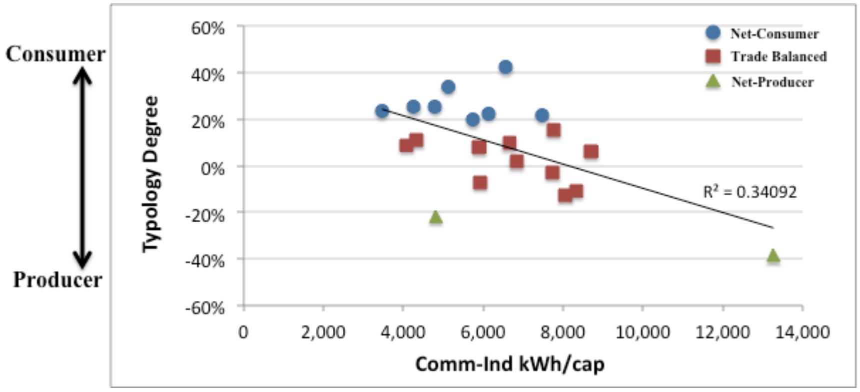


Figure 4-17: Correlation in community Typology Magnitude versus Total Commercial-Industrial Electricity Use per Capita.

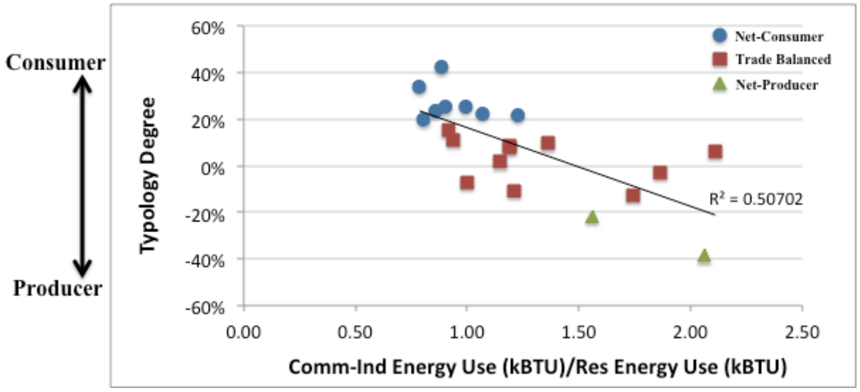


Figure 4-18: Correlation in community Typology Magnitude versus Commercial-Industrial Energy use (in kBTU) per Residential Energy Use (in kBTU).

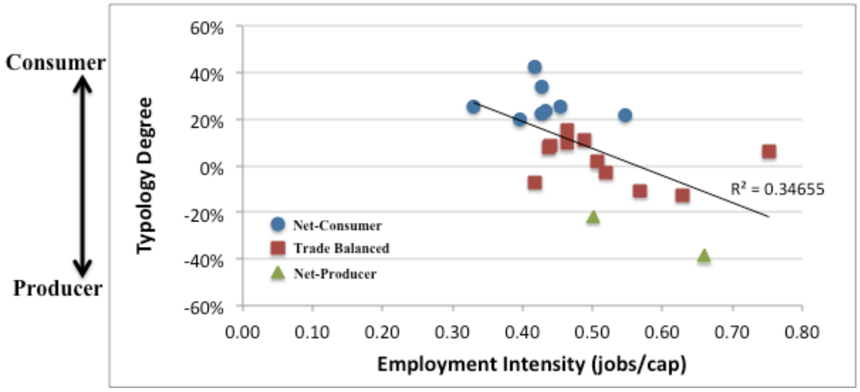


Figure 4-19: Correlation in community Typology Magnitude versus Employment Intensity.

4.3.3 Trans-Boundary Supply-Chains of Cities

The trans-boundary supply-chain footprints serving cities are computed using each city's calibrated IMPLAN model. We apply Equation 3-3, presented in chapter 3, to compute each city's supply-chain GHGs. Recall,

$$GHG^{CBF} = [B][TLO] + [EF^{use}] \times \{[F] + [M_F]\} + [B][L][M_{net}^{\inf ra}] + [B][L][M_{net}^{non-\inf ra}]$$

$$= [B][TLO] + [EF^{use}] \times \{[F] + [M_F]\} + [B][L][M_Z + M_F + E]$$

Following the equation, GHGs are divided into three broad categories: Territorial, trans-boundary supply-chains in Imports, and trans-boundary supply-chains in Exports. The first term of the equation, *(B)(TLO)*, represents territorial GHGs from the production in serving Local Consumption (F), and Exports (E). Namely,

$$[B][TLO] = [B][L_{local}][F+E] \qquad \textbf{Equation 4-1}$$

where, $\mathbf{L_{local}}$ is the respective city's local Leontief total requirements matrix. The other element comprising territorial GHGs are from direct energy (natural gas, gasoline, and diesel) use by households. Their sum equals Territorial GHGs for each city, shown as **IB** in Figure 4-20 thru Figure 4-22.

Trans-boundary GHGs embodied in imports (IM) either serve local industries and/or homes directly. Moreover, trans-boundary GHGs in imports serving local industries can be separated as production for local consumers, and production for exports, by multiplying these imports with the ratio of local outputs for consumers to total local output, {(L)(F)/(L)(TLO)}, by sector. These imports are further separated into infrastructures and non-infrastructures. Imports for each city are shown in the second bar labeled **IM** in Figure 4-20 thru Figure 4-22.

A third bar in the figures shows GHGs embodied in exports for each city. These exports represent the full supply-chain including local commercial-industrial activities exported, and their associated supply chains. In equation form,

$$[B][L_{US}][E] = [B][L_{local}][E] + [B][L_{US}][M_{Z,E}] \qquad \textbf{Equation 4-2}$$

where $\mathbf{L}_{US}$ is the US national Leontief matrix, $\mathbf{M}_{Z,E}$ are the imports to local commercial-industrial users for exports – estimated as discussed above, and $\mathbf{B}$ is the GHG intensity vector. As IO data does not split imports into production for local consumption versus that for exports, GHGs embodied in the supply-chains of exports using Equation 4-2 is compared to those estimated from the Export vector retrieved from the IO data for each city. Table 4-12 shows that our method for separating imports to local commercial-industrial users produces reasonable estimates of the full export supply-chain as many of the errors are below 15%. The few larger errors may in part be attributed to the technique or to L_{local}, which may not fully capture local production requirements. Thus we proceed in our analysis using this separation for illustrating the supply-chains of cities.

Table 4-12: GHGs embodied in Exports. Calculated vs. IMPLAN total Export vector.

City	$[\mathbf{B}][\mathbf{L}_{Local}][\mathbf{E}]$	$[\mathbf{B}][\mathbf{L}_{US}][\mathbf{M}_{Z,E}]$	$[\mathbf{B}][\mathbf{L}_{US}][\mathbf{E}]$: ***Calculated***	$[\mathbf{B}][\mathbf{L}_{US}][\mathbf{E}]$: ***IMPLAN***	**% Diff**
Collier	846,259	1,945,450	2,791,709	2,497,715	12%
Sarasota	461,173	2,204,421	2,665,593	1,975,204	35%
Snohomish	1,652,523	5,259,992	6,912,515	6,029,561	15%
Sacramento	3,960,186	5,508,879	9,469,065	8,484,080	12%
Broward	8,463,628	10,587,261	19,050,889	17,486,903	9%
Boulder	1,159,811	2,426,372	3,586,183	3,540,732	1%
Roanoke	287,268	747,155	1,034,424	1,027,715	1%
Westchester	5,744,472	4,040,164	9,784,636	10,113,098	-3%
Loudoun	2,408,795	2,556,284	4,965,079	4,511,936	10%
Napa	537,608	1,391,696	1,929,304	1,994,607	-3%
DVRPC	34,454,245	42,851,364	77,305,608	69,370,700	11%
NYC	36,555,053	29,317,184	65,872,237	81,597,118	-19%
Philadelphia	7,079,029	8,016,292	15,095,321	15,322,841	-1%
Denver	3,472,998	9,477,079	12,950,077	12,783,593	1%
Washoe	1,883,643	3,648,350	5,531,993	5,693,676	-3%
METRO	10,868,539	12,154,565	23,023,104	21,480,451	7%
Broomfield	269,670	1,239,401	1,509,071	1,544,245	-2%
Multnomah	8,520,606	9,172,289	17,692,895	18,161,154	-3%
Miami-Dade	26,190,073	10,546,429	36,736,502	34,536,417	6%
Tompkins	1,692,002	859,627	2,551,628	2,707,895	-6%
Routt	1,254,395	239,908	1,494,303	1,424,675	5%

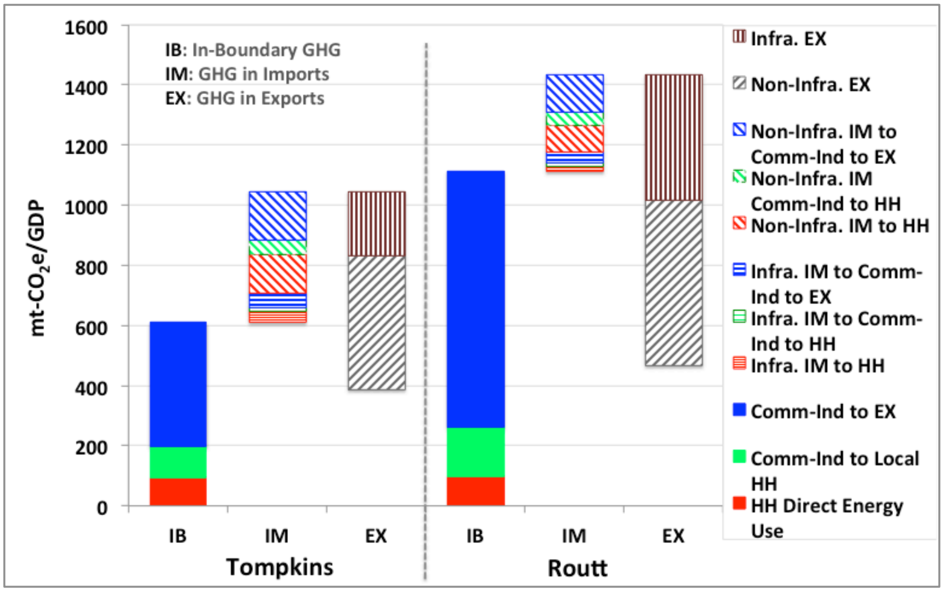


Figure 4-20: NET-PRODUCERS. GHGs relating to Territorial, Import, and Export supply-chains.

For net-producing cities, Figure 4-20 illustrates that territorial GHGs associated with these cities are larger (>600 mt-CO_2e/GDP) compared to GHGs embodied in imports. We also observe that a large portion of the total footprint is exported.

For trade-balanced cities (seen in Figure 4-21) it's noted that territorial GHGs are <400 mt-CO_2e/GDP, with the exception being Miami-Dade, which is a net-exporter of infrastructure, supporting both local consumption & exports. GHGs embodied in imports for some trade-balanced cities are roughly equal to their territorial GHG (e.g., NYC), while GHGs in imports for others are substantially larger (e.g., Napa). In these trade-balanced cities it's consistently observed that GHGs embodied in non-infrastructure imports are roughly equal to GHGs embodied in non-infrastructure exports. Across net-consumers (Figure 4-22) it's observed that GHGs embodied in imports are larger than territorial GHGs. Unlike the other city types, GHGs embodied in exports are small, and larger amounts of territorial GHGs are for local consumption.

In sum, these figures show that territorial GHGs are highest for net-producers, and lowest for net-consumers. GHGs embodied in imports are reversed, as they are highest for net-consumers, and lowest for net-producers. As for GHGs embodied in exports, they are largest for net-producers and trade-balanced cities.

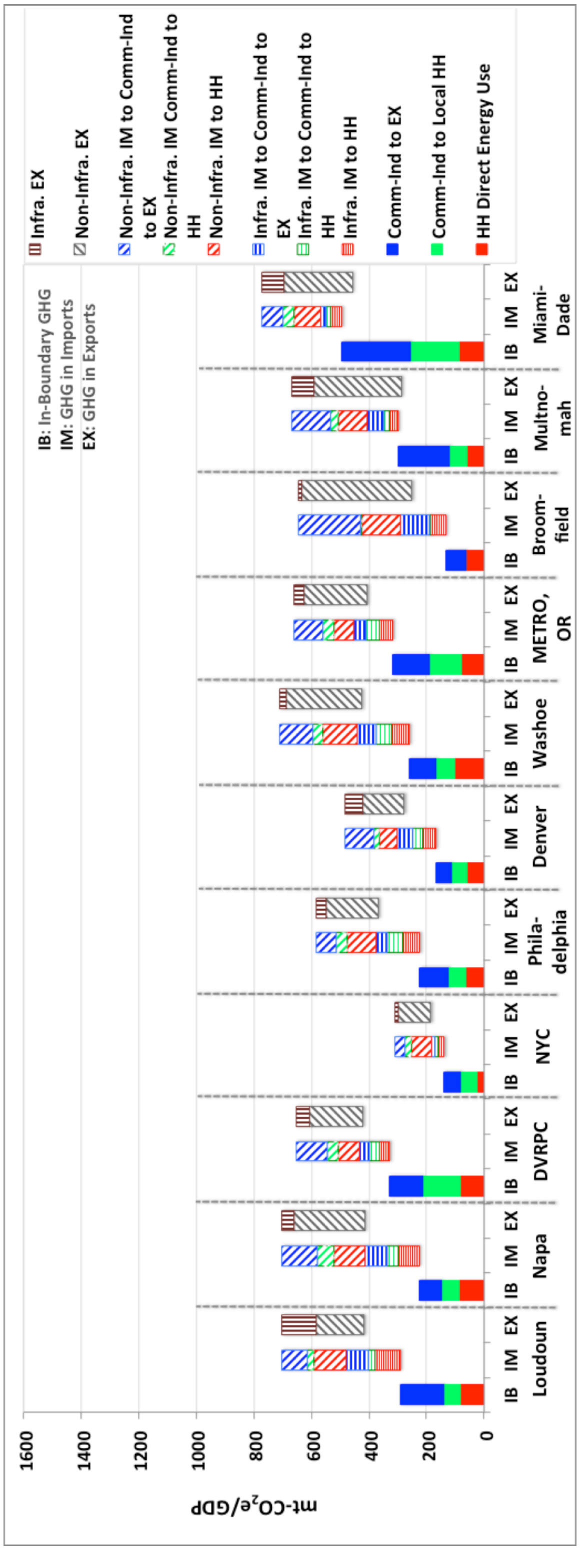


Figure 4-21: TRADE-BALANCED. GHGs relating to Territorial, Import, and Export supply-chains.

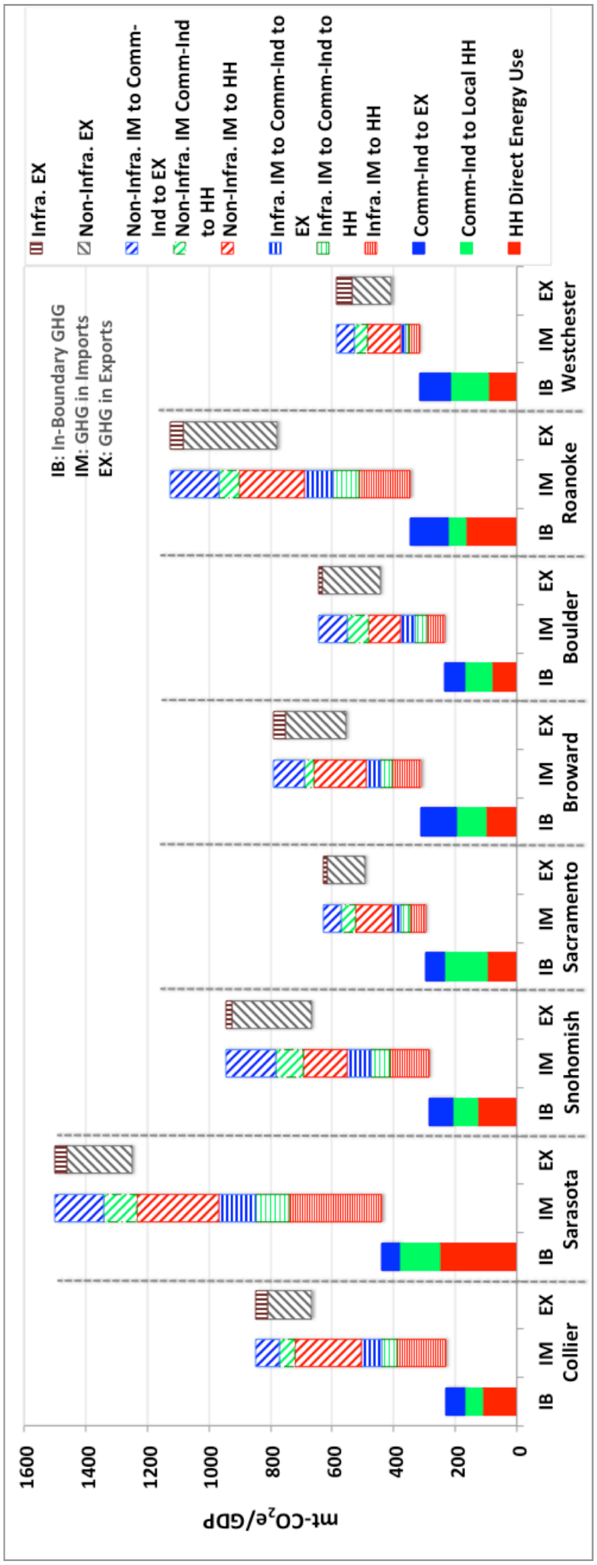


Figure 4-22: NET-CONSUMERS. GHGs relating to Territorial, Import, and Export supply-chains.

4.3.4 Comparing Coverage of Urban Metabolism by TBIF & CBF

Urban metabolism has been long studied within the literature of resource use in cities. The initial work by Abel Wolman was the catalyst as it defined the urban metabolism of cities as *"all commodities needed to sustain the city's inhabitants at home, work and at play"* (Wolman, 1965). However, due to the extreme data requirements for completing a full metabolic analysis of a city, others have only included selected materials, e.g., (Hanya & Ambe, 1976; Liang & Zhang, 2011; Newcombe, Kalma, & Aston, 1978; Sahely, Dudding, & Kennedy, 2003). This is a first of its kind analysis for cities, in that the metabolic structure for city economies with *all* of their associated supply-chains are included. Results are presented in terms of GHGs covered by Territorial (or in-boundary), Infrastructures (TBIF), and Consumption (CBF). The total footprint refers to all in-boundary GHG plus GHG embodied in imports.

$$\textbf{Total GHG Footprint} = \textbf{GHG}^{\textbf{IB}} + \textbf{GHG}^{\textbf{IM}} \qquad \textbf{Equation 4-3}$$

Recall that TBIF accounts for GHG from all territorial activity, along with GHG from allocated infrastructures supporting the city as a whole. On the other hand, CBF accounts for GHGs attributed to final consumption, regardless of production location. CBF also allocates out the full supply-chain of exports. The GHGs that neither TBIF nor CBF account for are those embodied in non-infrastructure imports to local businesses & industries, for exports. These are shown in blue cross-hatching in Figure 4-23. Of the total footprint these correspond to 12%, 17%, and 12% for net-producers, trade-balanced, and net-consumers, respectively, on average.

Comparing the coverage between TBIF and CBF for <u>net-producer</u> cities shows that on average, Territorial captures 68% of the total footprint, TBIF captures 75% of the total footprint, and CBF only captures 35%. The incremental portion of consumption not captured by TBIF is 13% of the footprint. However, the portion of export production not captured by CBF is 53%. See Figure 4-23, Figure 4-24, and Figure 4-27.

For trade-balanced cities, Territorial captures 42%, TBIF captures 63%, and CBF captures 57% of the total footprint, on average. The incremental portion of consumption not captured by TBIF is 20% of the total footprint. The portion of export production not captured by CBF equals 26% of the total footprint. See Figure 4-23, Figure 4-25, and Figure 4-28.

For net-consumer cities, Territorial captures 37%, TBIF captures 62%, and CBF captures 71% of the total footprint, on average. The incremental portion of consumption not captured by TBIF is 26% of the total footprint. The portion of export production not captured by CBF is 17% of the total footprint. See Figure 4-23, Figure 4-26, and Figure 4-29.

These results show that indeed the amount of the urban metabolism captured greatly depends on the lens with which the analysis is approached. TBIF captures all activity within the boundary along with GHGs embodied in infrastructure imports, although misses the additional non-infrastructure consumption to households. Meanwhile, CBF captures all the GHGs embodied in the supply-chains relating to consumption, but in the interim misses key aspects of local economies for exports – which are larger in balanced and net-producing cities. In total, TBIF captures more than 62% of the total footprint for all three-city types. However, the coverage of CBF depends on the city type, which on average can be as low as 35% or as high as 71%.

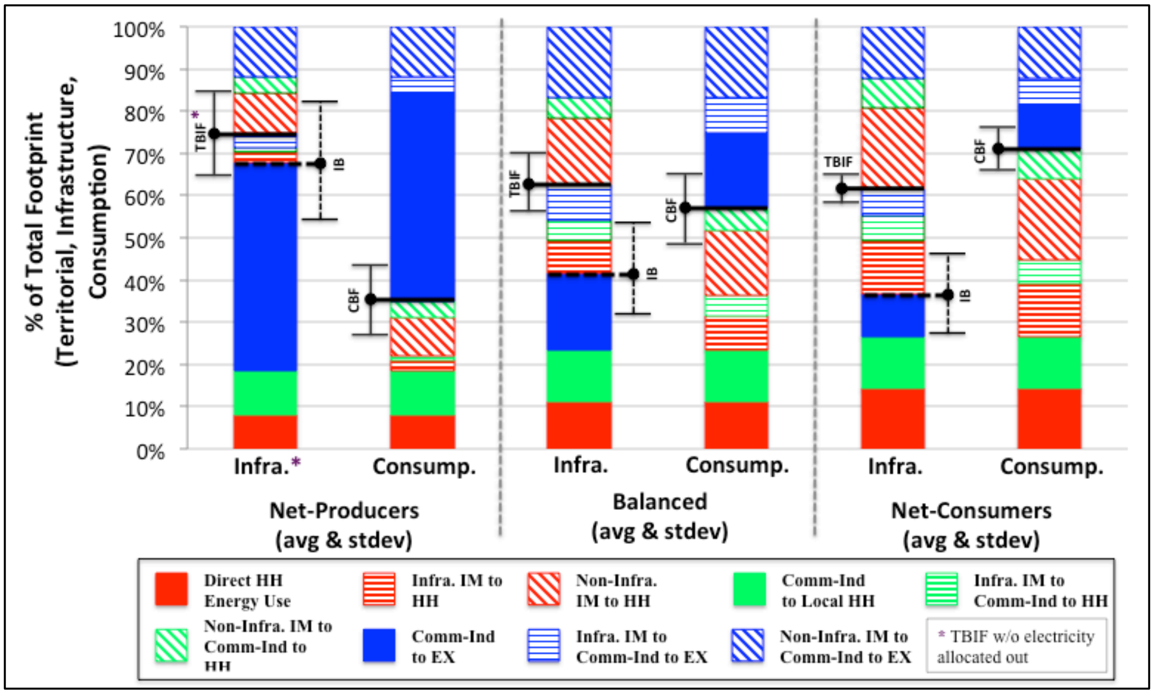


Figure 4-23: GHGs covered by TBIF and CBF, respectively. Shown as the average of cities by typology.

Coverage by Infrastructure (TBIF), by Typology:

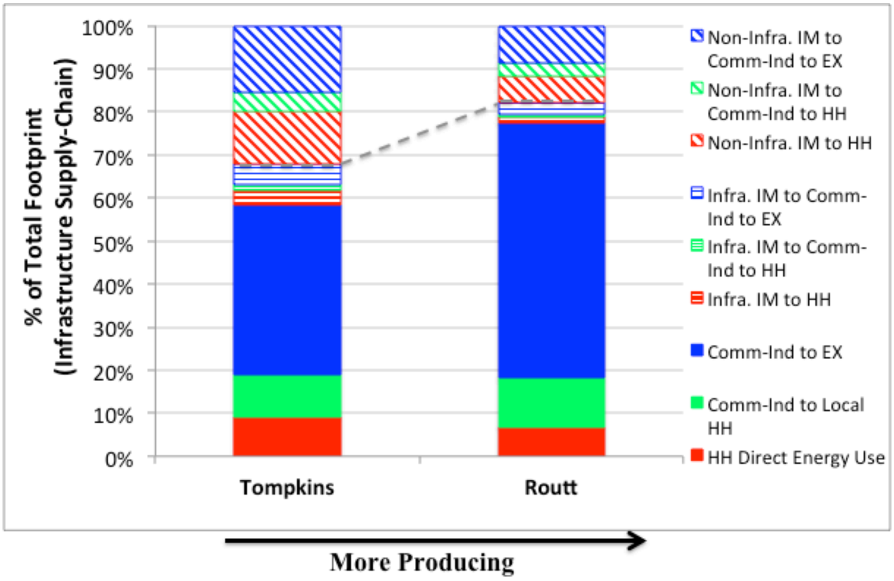


Figure 4-24: NET-PRODUCER - % of total footprint GHGs covered by infrastructure supply-chain.

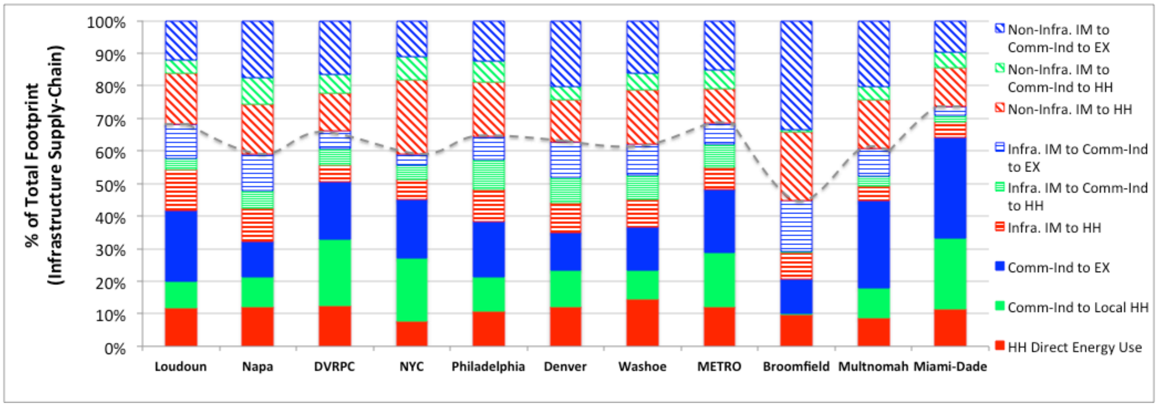


Figure 4-25: TRADE-BALANCED - % of total footprint GHGs covered by infrastructure supply-chain.

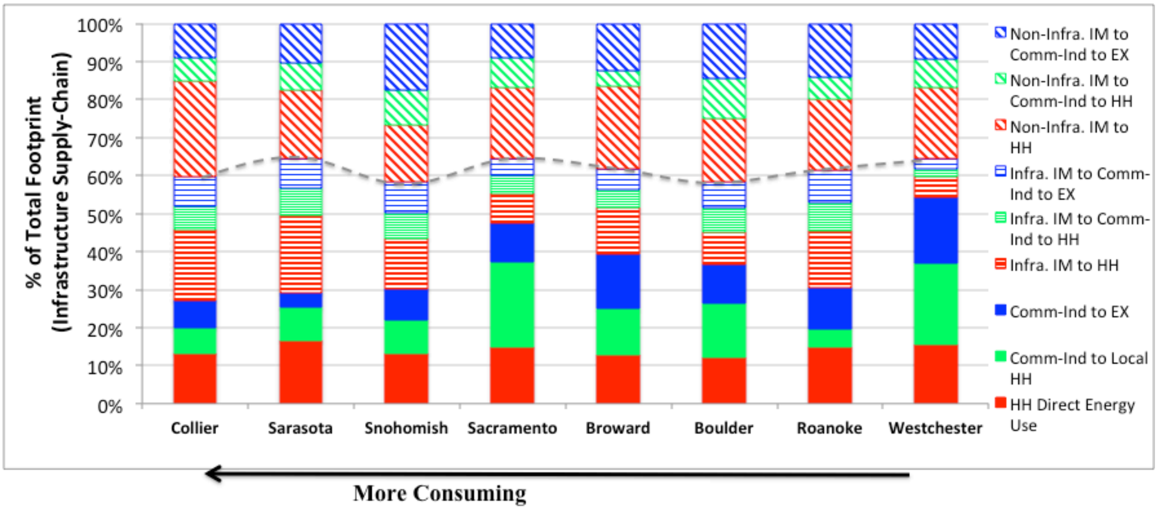


Figure 4-26: NET-CONSUMER - % of total footprint GHGs covered by infrastructure supply-chain.

Coverage by Consumption (CBF), by Typology:

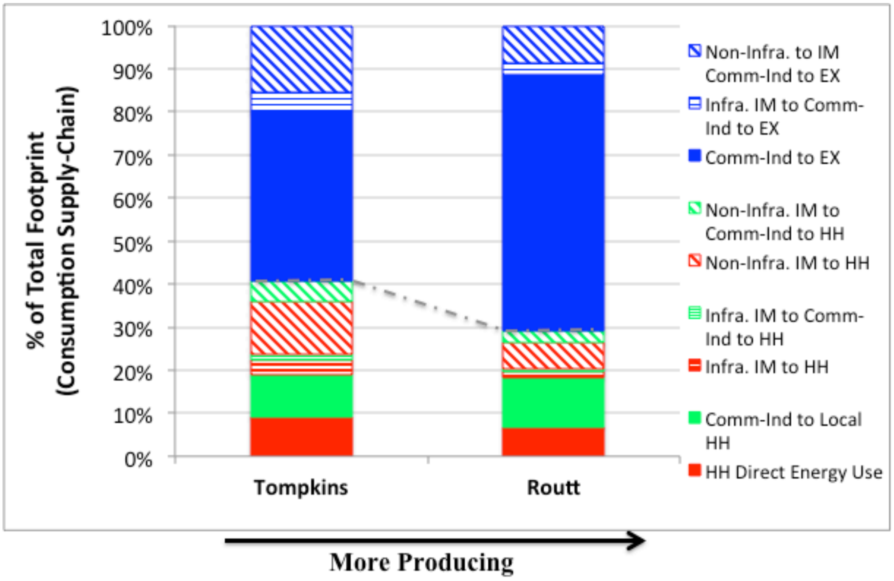


Figure 4-27: NET-PRODUCER - % of total footprint GHGs covered by consumption supply-chain.

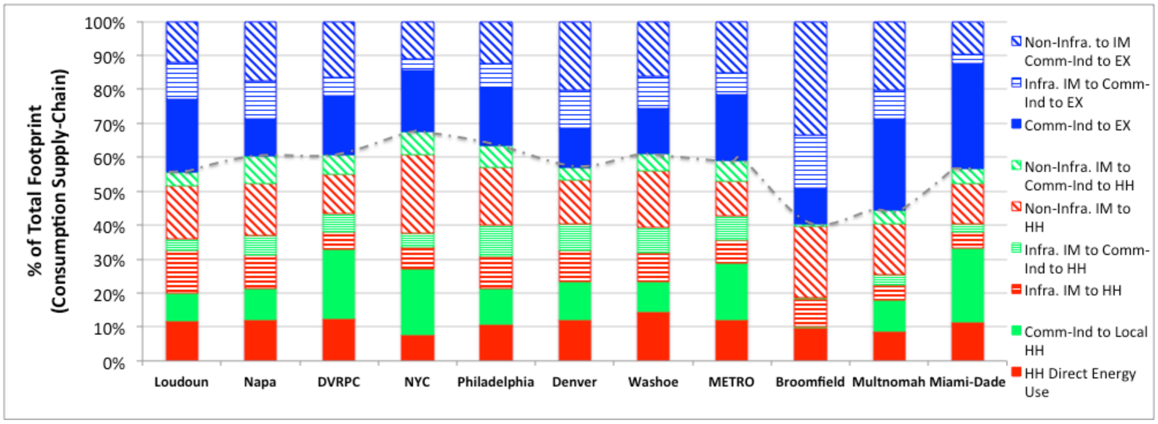


Figure 4-28: TRADE-BALANCED - % of total footprint GHGs covered by consumption supply-chain.

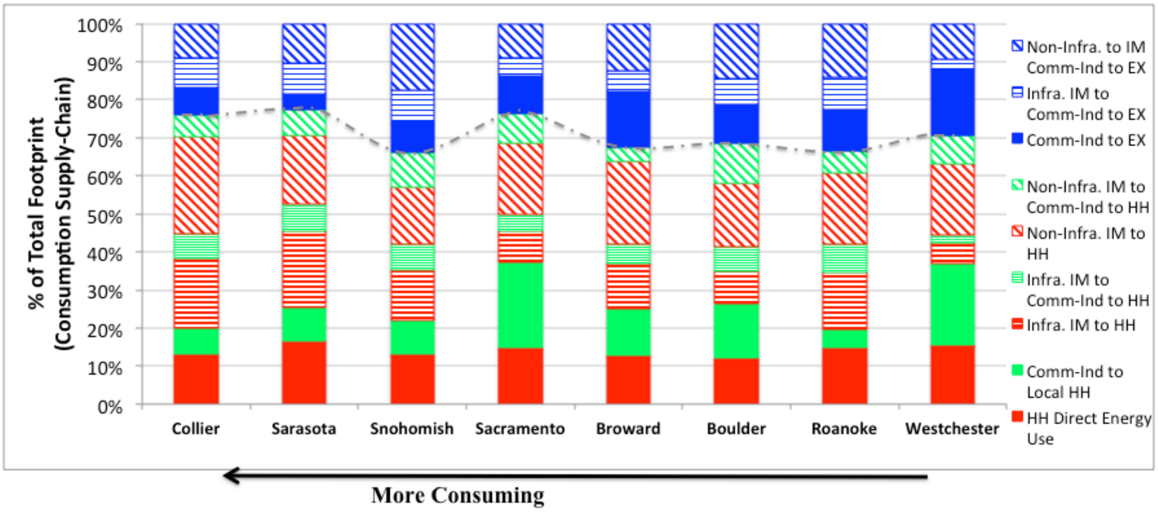


Figure 4-29: NET-CONSUMER - % of total footprint GHGs covered by consumption supply-chain.

4.3.5 Metrics for Comparing GHGs Associated with Cities

Exploring suitable metrics for comparing GHGs associated with cities builds on the data results described above. The key question asked here is whether cities with lower GHG footprints reported by a certain metric (e.g., GHG^{TBIF} or GHG^{CBF}) truly represent greater urban efficiency.

The first step in our method is to construct an urban efficiency index (UEI) that represents the major energy efficiency characteristics of a city. We propose an UEI composed of three key attributes: 1) production efficiency, 2) household energy efficiency, and 3) transportation system efficiency. Energy use is converted to GHG using national average emission factors for electricity (0.64 kg-CO2e/kWh) and natural gas (5.4 kg-CO2e/therm). The resulting commercial-industrial GHGs are normalized by GDP, while Residential GHGs are normalized by capita to represent production efficiency and household energy efficiency, respectively. Because a city's transportation serves both private commutes and job related travel, the transportation system efficiency is represented as motor vehicle miles traveled (VMT) per *residents+jobs*. The composite index for a given city is the sum of the three attributes.

Table 4-13: Attributes and units of the Urban Efficiency Index (UEI).

Attribute of the UEI	Units of Attribute
Production Efficiency	GHGs from Commercial-Industrial Energy Use per GDP **(mt-CO2e/GDP)**
Household Energy Efficiency	GHGs from Household Energy Use per resident **(mt-CO2e/capita)**
Transportation System Efficiency	VMT's per residents plus jobs **(VMT/(res+jobs))**

In-sample comparisons are performed by evaluating the correlations between each of the ten metrics presented in Table 4-14, versus the composite urban energy efficiency index (UEI) for each of the 21 cities. By doing so we aim to answer whether cities with lower GHG indeed represent greater urban efficiency.

Table 4-14: Metrics evaluated for comparing GHGs associated with cities against the UEI.

GHG Accounting Method	**GHGs**	**Metric and Units**	
		Per GDP (community GDP)	**Per capita (resident population)**
Territorial (in-boundary)	Purely Territorial **(GHG^{IB})**	GHG^{IB}/GDP	GHG^{IB}/cap
Various versions of TBIF	Purely Territorial + Electricity Allocated **($\text{GHG}^{\text{TBIF Scope 1+2}}$)**	$\text{GHG}^{\text{Scope 1+2}}$/GDP	$\text{GHG}^{\text{Scope 1+2}}$/cap
	Plus Scope 3 w/o Allocating **($\text{GHG}^{\text{TBIF Scope 1+2+3}}$)**	$\text{GHG}^{\text{Scope 1+2+3}}$/GDP	$\text{GHG}^{\text{Scope 1+2+3}}$/cap
	Scope 3 w/ Allocating **($\text{GHG}^{\text{TBIF, modeled}}$)**	$\text{GHG}^{\text{Scope 1+2+3*}}$/GDP	$\text{GHG}^{\text{Scope 1+2+3*}}$/cap
CBF	Consumption-Based GHGs **(GHG^{CBF})**	GHG^{CBF}/GDP	GHG^{CBF}/cap

* Scope 3 is now allocated based on use

The computed UEIs are shown in Table 4-15. City identities have been suppressed, and column 1 of the table shows each city's unique identifier code. The last column is the composite index, and is the independent variable used in the evaluation.

Table 4-15: UEI for 21 US cities.

City ID Code	Production Efficiency Index	Household Efficiency Index	Transportation System Efficiency Index	Composite Index
A	0.71	0.78	1.05	**2.54**
B	0.64	0.71	1.04	**2.39**
C	1.02	1.12	0.97	**3.12**
D	0.88	0.99	0.86	**2.73**
E	0.75	0.84	0.87	**2.45**
F	1.32	1.50	1.17	**3.99**
G	1.02	1.39	1.38	**3.80**
H	1.65	1.32	1.49	**4.45**
I	0.97	1.08	1.21	**3.26**
J	0.87	0.97	1.09	**2.93**
K	1.14	0.94	0.98	**3.06**
L	1.13	0.75	0.79	**2.67**
M	0.52	0.78	1.21	**2.50**
N	0.99	0.92	0.98	**2.89**
O	1.17	0.82	0.94	**2.92**
P	1.06	0.80	0.49	**2.35**
Q	1.50	1.51	1.26	**4.27**
R	0.97	1.26	0.93	**3.17**
S	1.18	0.98	1.03	**3.18**
T	0.44	0.55	0.35	**1.34**
U	1.07	1.00	0.91	**2.98**

Correlations between the UEI and each of the ten metrics are used to evaluate suitable metrics for comparing GHGs associated with cities. The progression from Figure 4-30 towards Figure 4-33 illustrates that GHGs normalized per capita (figures ***b***) do not capture all activities (production and homes), as observed by consistently low correlations. Meanwhile, the same progression for GHGs normalized by GDP (figures ***a***) shows that GHGs compared to a city's economic development (GHG/GDP) are more representative of all activities located in a city (production and homes). It's observed that a per capita metric correlates significantly better when accounting for consumption-based GHGs (R^2=0.41, Figure 4-34), suggesting that per capita is better suited for representing GHGs from household consumption. The strong correlation (R^2=0.76, Figure 4-35), between consumption-based GHGs and expenditures shows that GHG^{CBF} more directly illustrates the willingness of a city's residents to consume.

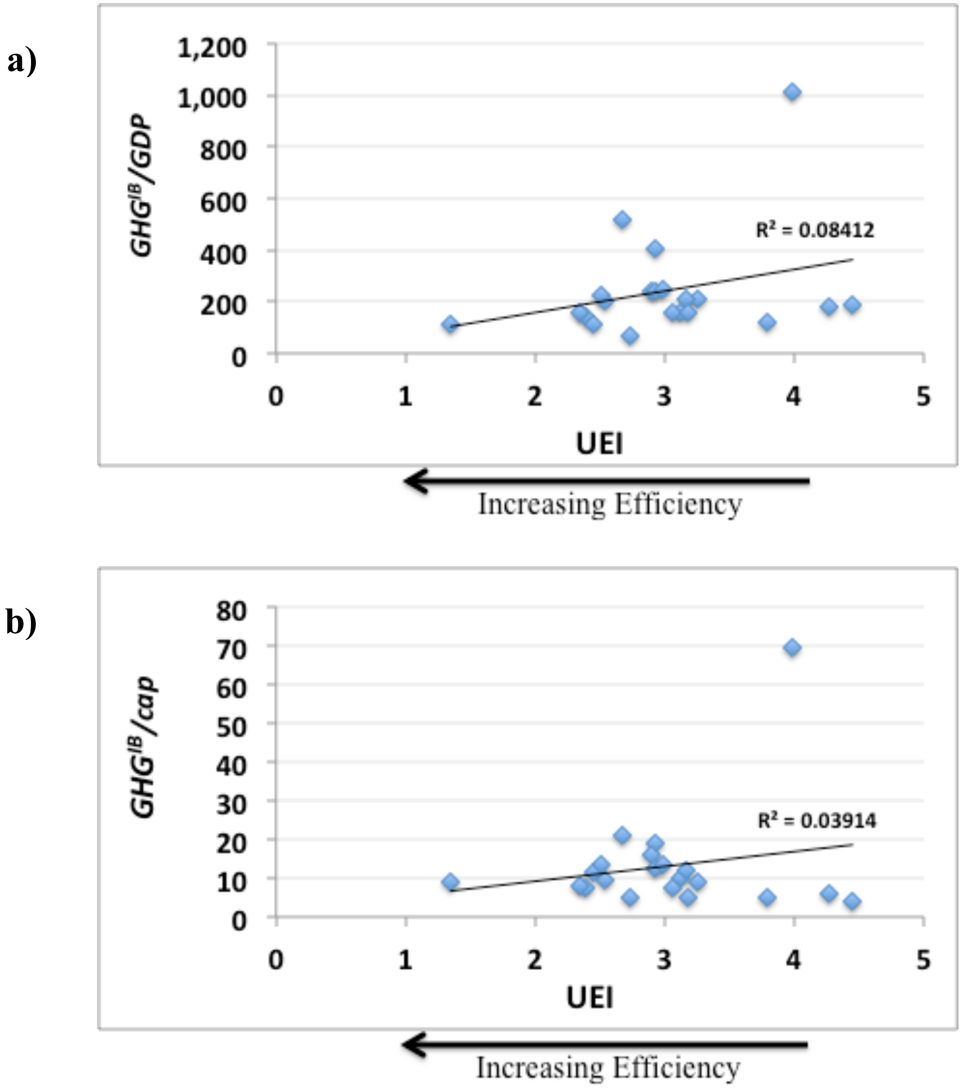


Figure 4-30: Metric #1 – Correlation of Territorial GHGs vs. UEI. a) per GDP, and b) per capita.

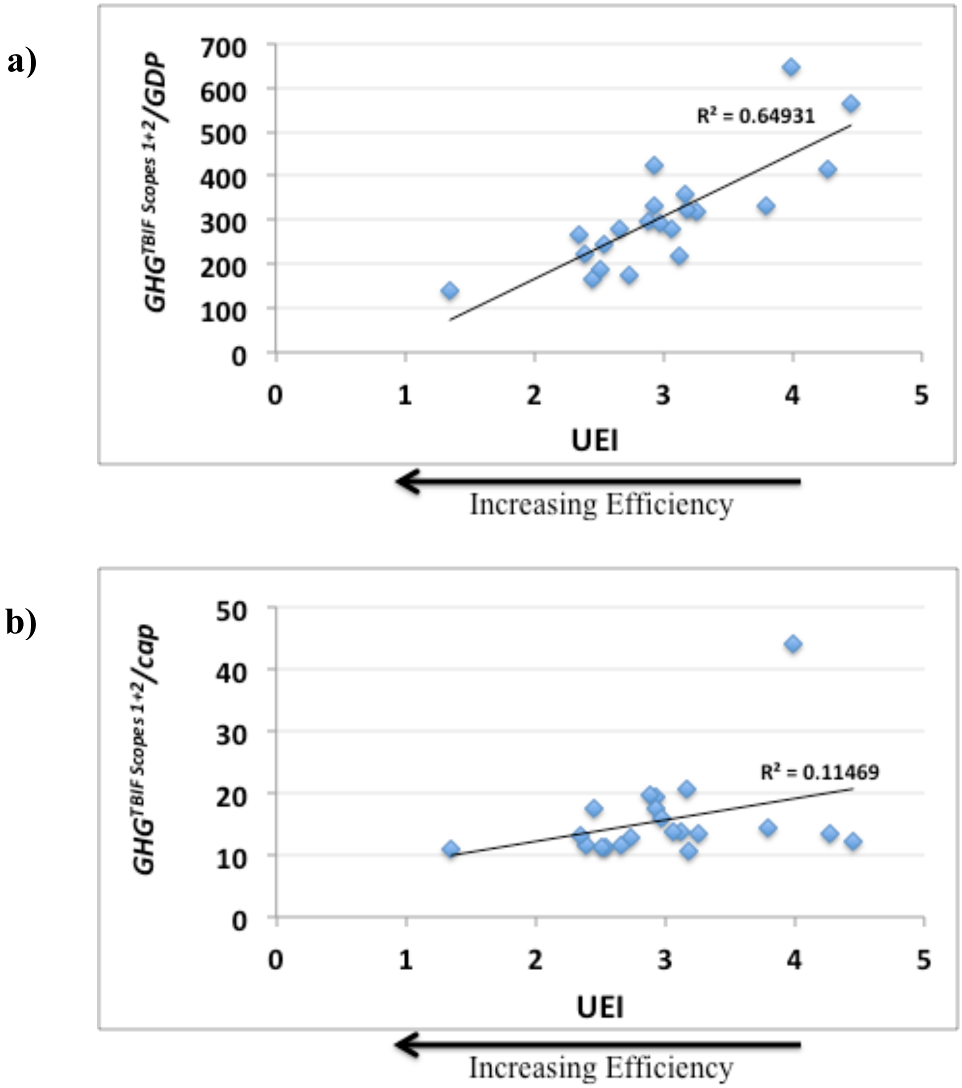


Figure 4-31: Metric #2 – Correlation of Scope 1+2 GHGs vs. UEI. a) per GDP, and b) per capita.

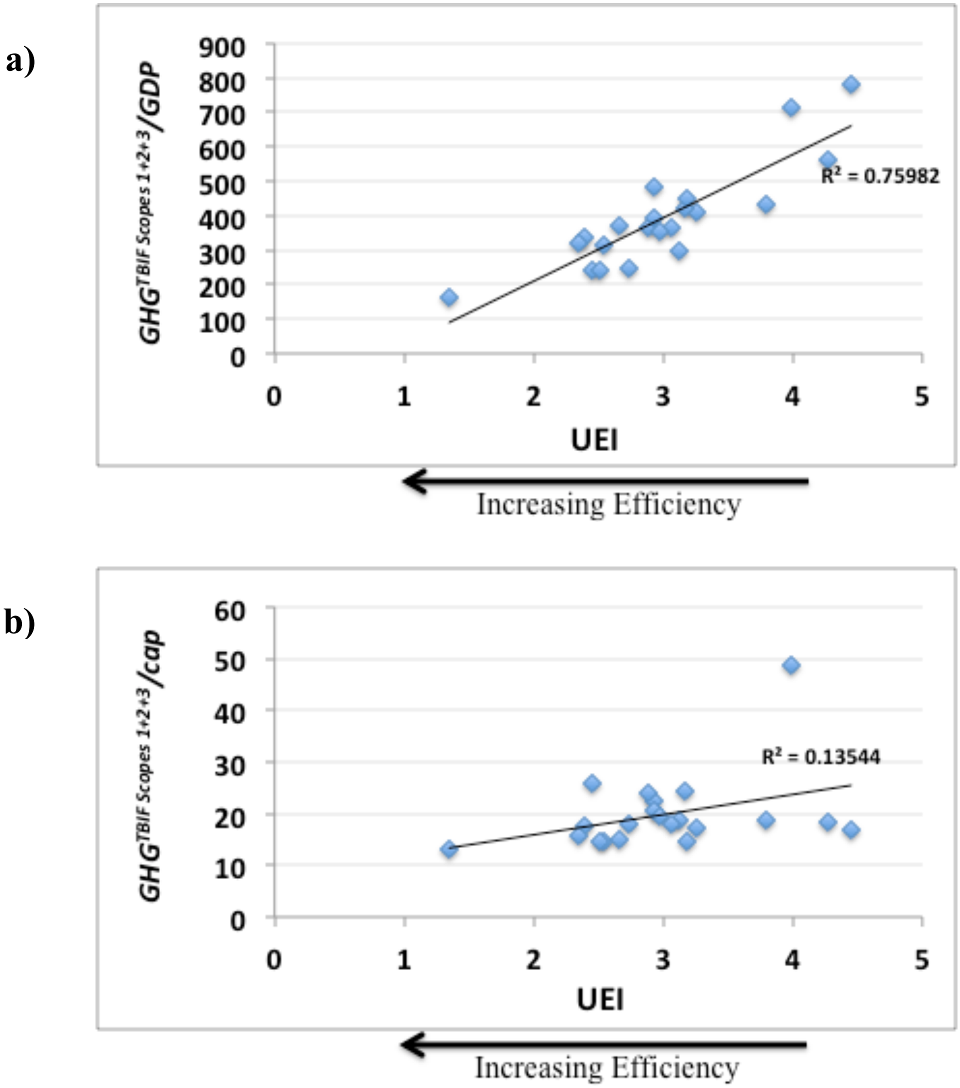


Figure 4-32: Metric #3 – Correlation of Scope 1+2+3 GHGs vs. UEI. a) per GDP, and b) per capita.

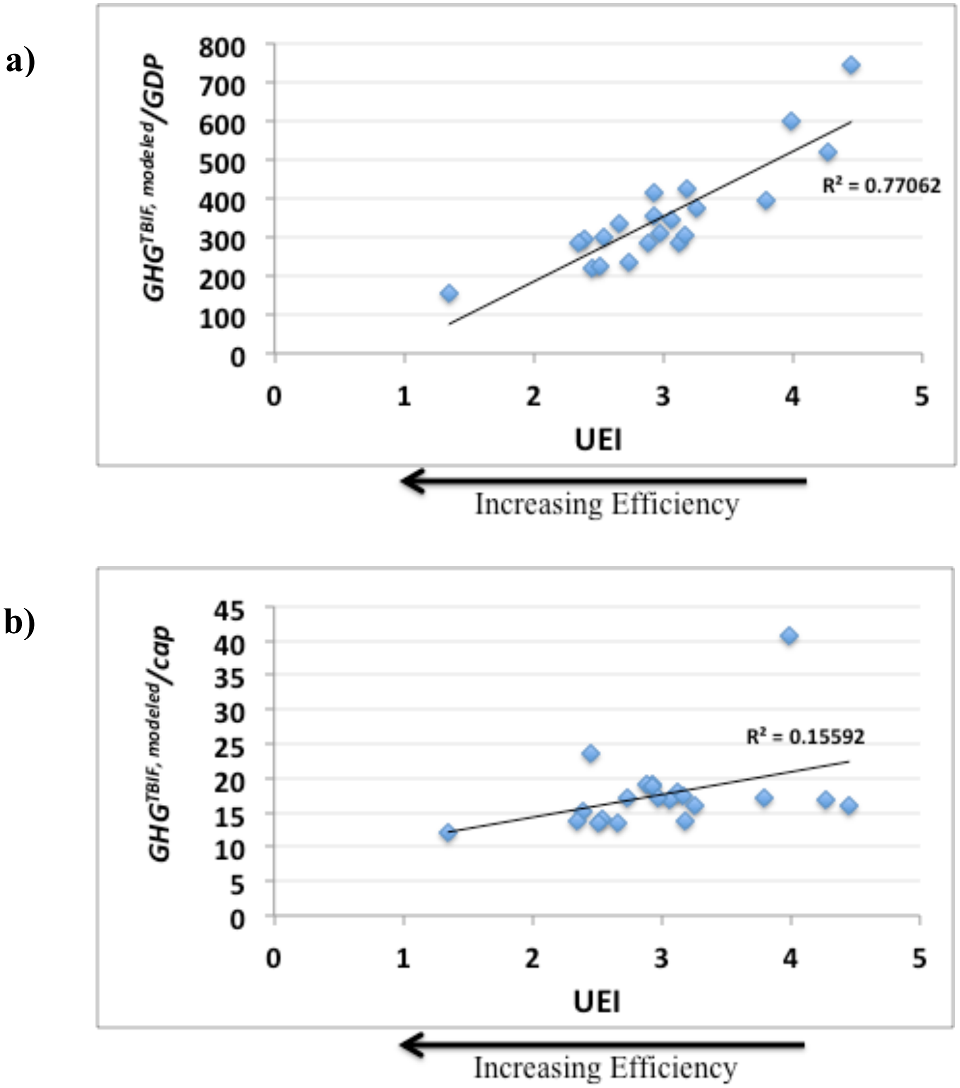


Figure 4-33: Metric #4 – Correlation of TBIF GHGs vs. UEI. a) per GDP, and b) per capita.

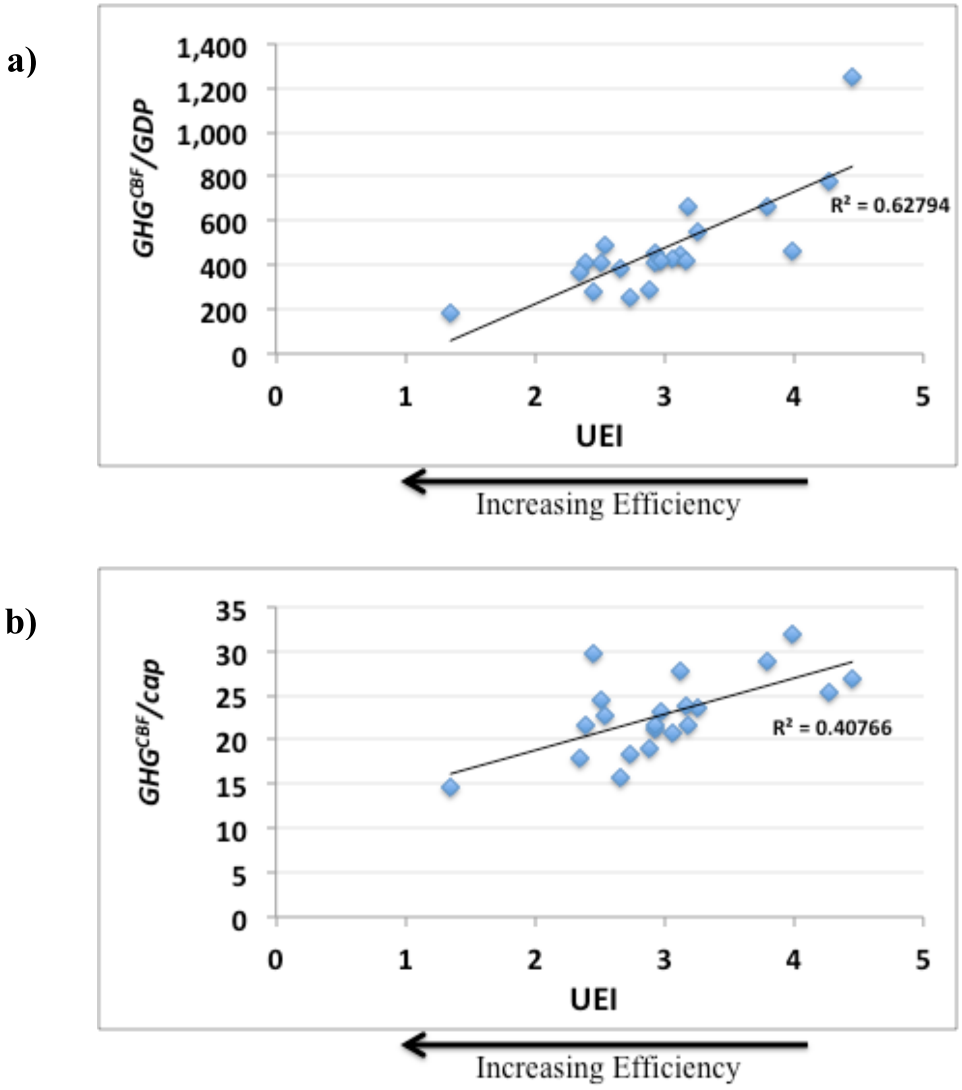


Figure 4-34: Metric #5 – Correlation of Consumption-Based GHGs vs. UEI. a) per GDP, and b) per capita.

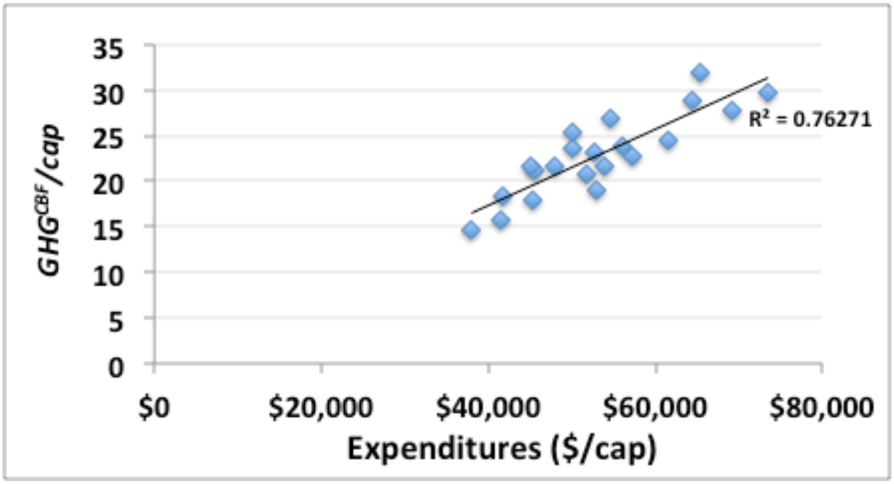


Figure 4-35: Correlation of GHG^{CBF}/cap vs. Final Consumption Expenditures ($/cap).

This analysis shows that territorial GHGs are ineffective for comparing cities whether per GDP or per capita. $GHG^{Scopes1+2}$ remains a production-based accounting type of approach; hence GHG/GDP is a good metric to compare production efficiencies of cities. Correlations improve with electricity allocated (R^2=0.65), to including food agriculture & petroleum refining (R^2=0.76). Additional items had small impact on the correlation. Being that our sample of 21 cities was skewed towards net-consumer cities (only included 2 net-producing cities), it may be that including a larger amount of producing cities would reduce the correlation of GHG^{CBF}/GDP with UEI, and increase the correlation of GHG^{TBIF}/GDP with UEI.

Table 4-16: Impacts of infrastructures, beyond electricity, having the most impact on urban efficiency.

Infrastructure Sector	**R^2 (w/o allocation)**	**R^2 (w/ allocation)**
Fuel Refining	0.698	0.661
Iron/Steel	0.676	0.667
Air Travel	0.671	0.669
Food Agriculture	0.665	0.695
Cement	0.664	0.655

4.4 Conclusion

The meta-analysis revealed several new insights that can lead to the overall understanding of the urban metabolism for cities. Upon reviewing energy use and GHGs reported by US cities, we learn that a lack of protocols may attribute to cities reporting high quality building energy end-use, and underreporting GHGs from industrial processes. Pollutants from industrial processes are currently only accounted for by national bodies (e.g., TRI). Therefore this research used the modified IMPLAN IO tables as a model for comparing the three GHG emission accounting methods.

As a result from the four specific objectives in this chapter, the following highlights the major findings:

Objective 1: A series of correlations show that electricity generation, fuel refining, air travel, and the production of food, cement, and iron/steel, each are infrastructures that are important to economic development of cities. Thus we recommend these infrastructures to be allocated to cities based on “use” to a city’s residential-commercial-industrial sectors.

Objective 2: Using our typology degree reveals that larger cities tend to approach trade-balanced. Thus the world’s mega-cities may be trade-balanced as well, in which case TBIF could be used to measure the GHG emissions footprint of these cities. It’s also shown that perhaps the ratio of commercial-industrial energy use to household energy use can serve as a fast approach for measuring the typology of city.

Objective 3: The size and nature of the supply-chains serving cities shows that Territorial GHGs can be as small as 37% of the total footprint for net-consumer cities, and as large as 68% for net-producers. TBIF is steady capturing between 62% - 68% of the total footprint, while CBF depends on city typology, and captures between 35% - 71% of the total footprint.

Objective 4: Through an evaluation of ten metrics each compared with an urban energy efficiency index (UEI), we show that Territorial GHG is not suitable for comparing GHG associated with cities by any metric. However, TBIF by GDP is suitable for representing the urban efficiencies of cities, and should be used when comparing production-based GHGs. On the other hand, CBF by capita should be used when comparing consumption-based GHGs.

Supplementary Information (SI) – Chapter 4

S 4-1 – Commercial-Industrial Energy Use Efficiencies for 21 cities

	Commercial-Industrial		
County	**kWh/GDP/yr**	**therms/GDP/yr**	**kBTU/GDP/yr**
NYC, NY	51,750	1,727	349,235
DVRPC, PA/NJ	122,185	4,676	884,403
Miami-Dade, FL	130,071	308	474,581
Broward, FL	143,410	507	539,977
Oregon METRO, OR	142,592	4,035	889,988
Philadelphia, PA	127,266	3,956	829,744
Sacramento, CA	90,911	1,931	503,276
Westchester, NY	57,591	2,514	447,802
Multnomah, OR	121,085	3,463	759,421
Snohomish, WA	147,025	3,704	871,973
Denver, CO	80,201	3,916	665,176
Washoe, NV	143,502	3,546	844,146
Sarasota, FL	234,714	1,824	983,190
Collier, FL	150,483	536	567,077
Boulder, CO	120,879	4,042	816,561
Loudoun, VA	135,401	1,474	609,383
Napa, CA	81,067	1,823	458,903
Tompkins, NY	118,094	6,209	1,023,756
Roanoke, VA	175,378	6,165	1,214,728
Broomfield, CO	113,769	2,361	624,259
Routt, CO	170,398	3,495	930,815
US	162,380	7,849	1,338,748

S 4-2 – Residential Energy Use Efficiencies for 21 cities

	Residential		
County	**kWh/cap/mo**	**therms/cap/mo**	**kBTU/cap/mo**
NYC, NY	144	14	1,928
DVRPC, PA/NJ	326	19	2,962
Miami-Dade, FL	443	3	1,822
Broward, FL	518	0.2	1,788
Oregon METRO, OR	303	11	2,108
Philadelphia, PA	205	21	2,827
Sacramento, CA	276	12	2,148
Westchester, NY	216	19	2,612
Multnomah, OR	337	13	2,412
Snohomish, WA	385	11	2,365
Denver, CO	233	20	2,805
Washoe, NV	282	20	2,979
Sarasota, FL	630	1	2,233
Collier, FL	672	0	2,314
Boulder, CO	349	23	3,481
Loudoun, VA	482	15	3,164
Napa, CA	229	13	2,115
Tompkins, NY	242	14	2,227
Roanoke, VA	534	23	4,093
Broomfield, CO	295	21	3,143
Routt, CO	531	23	4,082
US	378	14	2,665

S 4-3 – Transportation System Efficiencies for 21 cities

	VMT
County	**VMT/(res+jobs)/day**
NYC, NY	5.8
DVRPC, PA/NJ	14.9
Miami-Dade, FL	17.8
Broward, FL	19.8
Oregon METRO, OR	15.4
Philadelphia, PA	8.0
Sacramento, CA	17.2
Westchester, NY	19.7
Multnomah, OR	16.0
Snohomish, WA	16.8
Denver, CO	14.2
Washoe, NV	16.0
Sarasota, FL	24.3
Collier, FL	22.6
Boulder, CO	15.9
Loudoun, VA	15.2
Napa, CA	17.0
Tompkins, NY	12.9
Roanoke, VA	20.6
Broomfield, CO	14.1
Routt, CO	19.2
US	20

S 4-4 – Corresponding Metropolitan Statistical Areas (MSA) for the 21 US City-County's in this analysis.

County	Metropolitan Statistical Area (MSA)
NYC, NY	New York-Northern New Jersey-Long Island, NY-NJ-PA
DVRPC, PA/NJ	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD
Miami-Dade, FL	Miami-Fort Lauderdale-Pompano Beach, FL
Broward, FL	Miami-Fort Lauderdale-Pompano Beach, FL
Oregon METRO, OR	Portland-Vancouver-Beaverton, OR-WA
Philadelphia, PA	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD
Sacramento, CA	Sacramento--Arden-Arcade--Roseville, CA
Westchester, NY	New York-Northern New Jersey-Long Island, NY-NJ-PA
Multnomah, OR	Portland-Vancouver-Beaverton, OR-WA
Snohomish, WA	Seattle-Tacoma-Bellevue, WA
Denver, CO	Denver-Aurora-Broomfield, CO
Washoe, NV	Reno-Sparks, NV
Sarasota, FL	Bradenton-Sarasota-Venice, FL
Collier, FL	Naples-Marco Island, FL
Boulder, CO	Denver-Aurora-Broomfield, CO
Loudoun, VA	Washington-Arlington-Alexandria, DC-VA-MD-WV
Napa, CA	Napa, CA
Tompkins, NY	Ithaca, NY
Roanoke, VA	Roanoke, VA
Broomfield, CO	Denver-Aurora-Broomfield, CO
Routt, CO	N/A. Assumed state averages where needed.

S 4-5 – For 21 US cities, household consumption is 70% of total final consumption, on average.

CITY	Total HH	Total Other FC	%HH of FC
NYC	$372,897	$105,758	**78%**
DVRPC	$211,392	$78,646	**73%**
Miami-Dade	$75,662	$33,215	**69%**
Broward	$63,307	$24,845	**72%**
METRO	$53,656	$23,142	**70%**
Philadelphia	$46,957	$18,715	**72%**
Sacramento	$42,152	$36,407	**54%**
Westchester	$44,289	$14,073	**76%**
Multnomah	$25,668	$12,103	**68%**
Snohomish	$20,275	$9,889	**67%**
Denver	$26,139	$17,107	**60%**
Washoe	$15,656	$5,587	**74%**
Sarasota	$15,439	$4,778	**76%**
Collier	$15,952	$4,361	**79%**
Boulder	$10,554	$8,971	**54%**
Loudoun	$9,958	$5,636	**64%**
Napa	$4,845	$2,361	**67%**
Tompkins	$2,999	$1,189	**72%**
Roanoke	$3,136	$795	**80%**
Broomfield	$1,526	$713	**68%**
Routt	$762	$649	**54%**
		Average =	**70%**

S 4-6 – Additional correlations between GDP and Use/Exports

Remaining Infrastructure Correlations (not shown above)

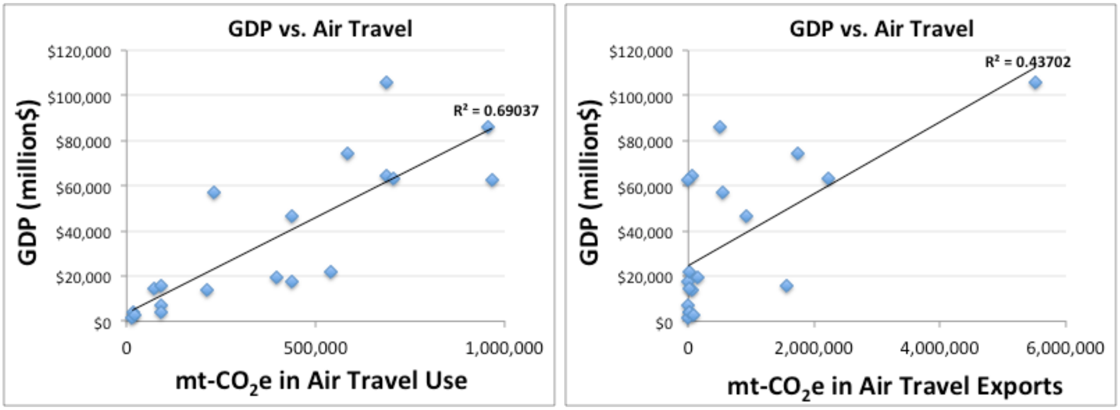


Figure S4-6a: Air Travel - GDP vs. GHGs from Use (left) and Export (right).

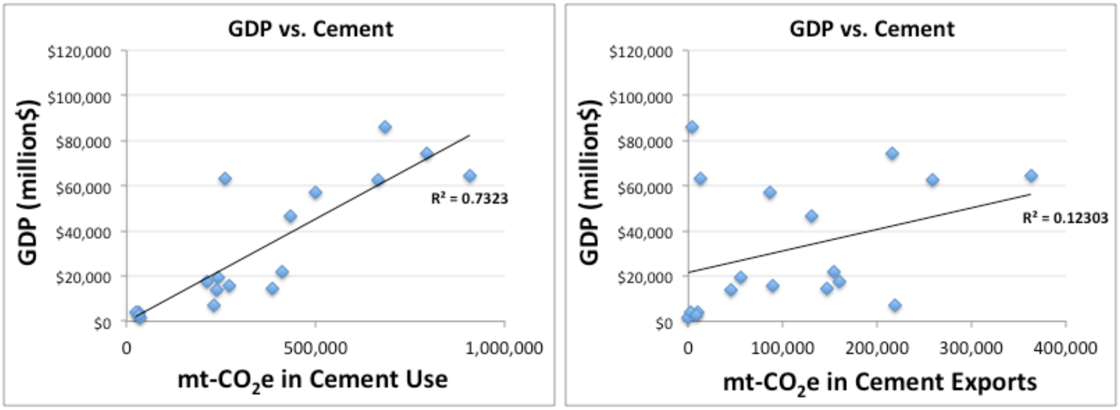


Figure S4-6b: Cement - GDP vs. GHGs from Use (left) and Export (right).

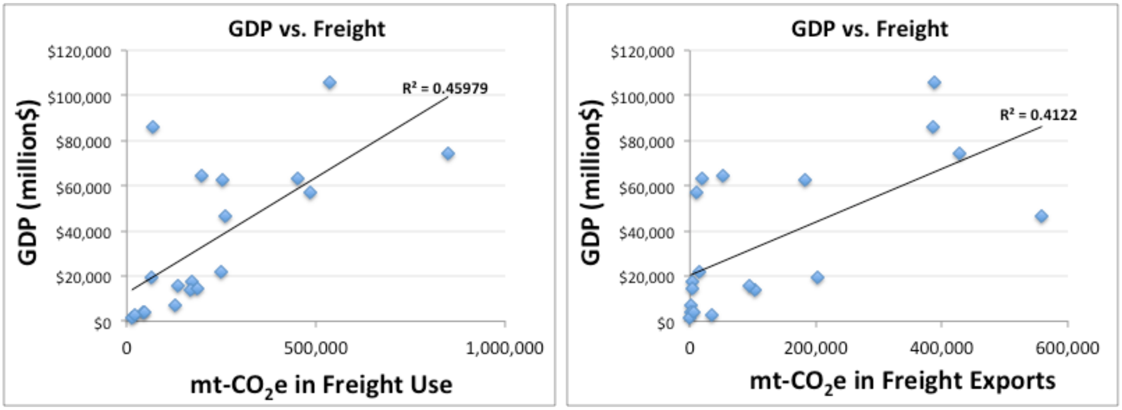


Figure S4-6c: Freight - GDP vs. GHGs from Use (left) and Export (right).

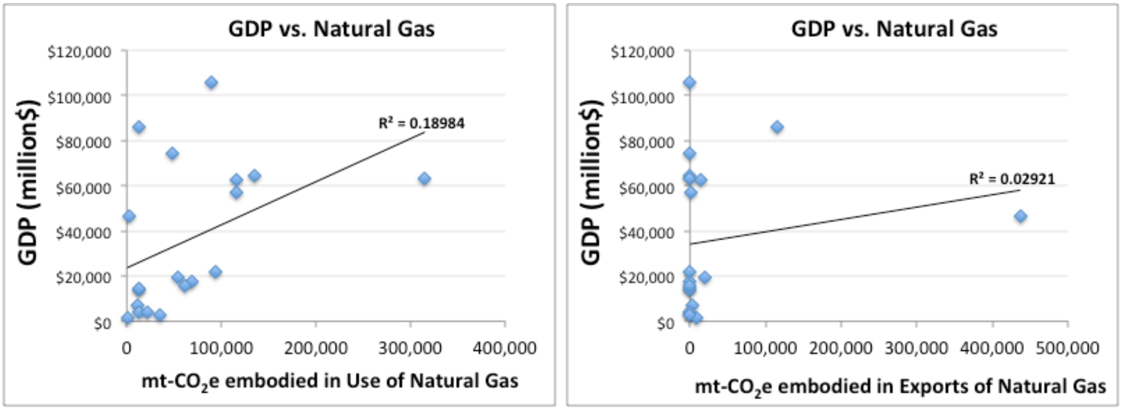


Figure S4-6d: Natural Gas - GDP vs. GHGs from Use (left) and Export (right).

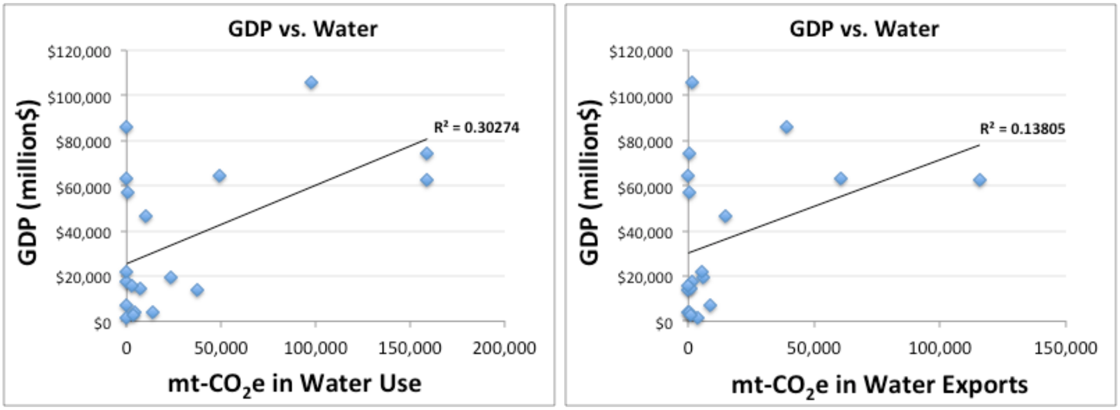


Figure S4-6e: Water/WW - GDP vs. GHGs from Use (left) and Export (right).

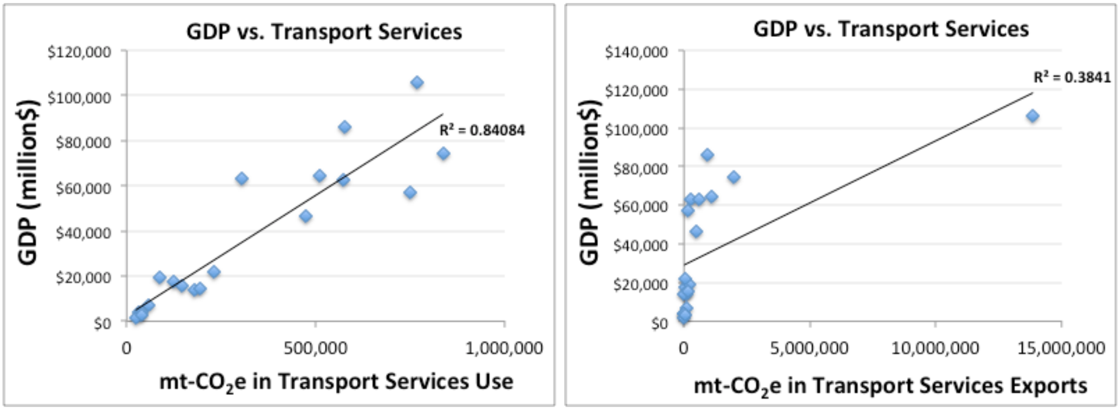


Figure S4-6f: Transport Services - GDP vs. GHGs from Use (left) and Export (right).

Remaining Non-Infrastructure Correlations (not shown above)

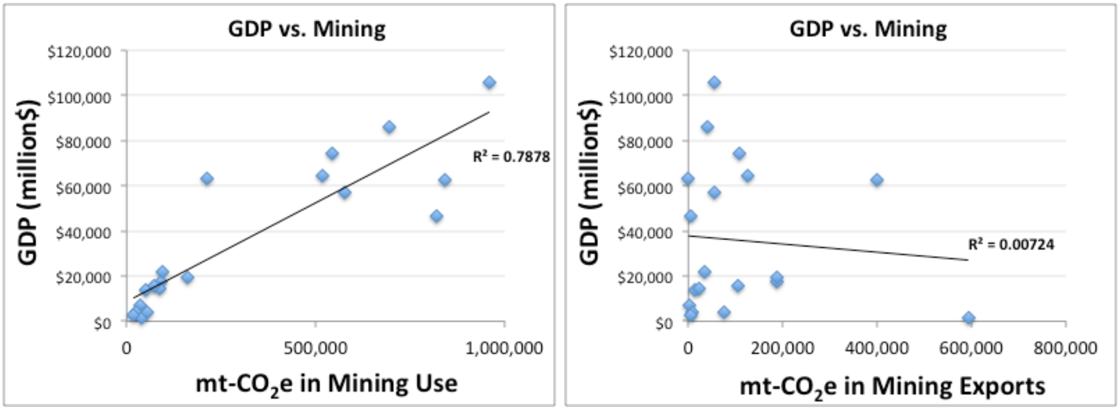


Figure S4-6g: Mining - GDP vs. GHGs from Use (left) and Export (right).

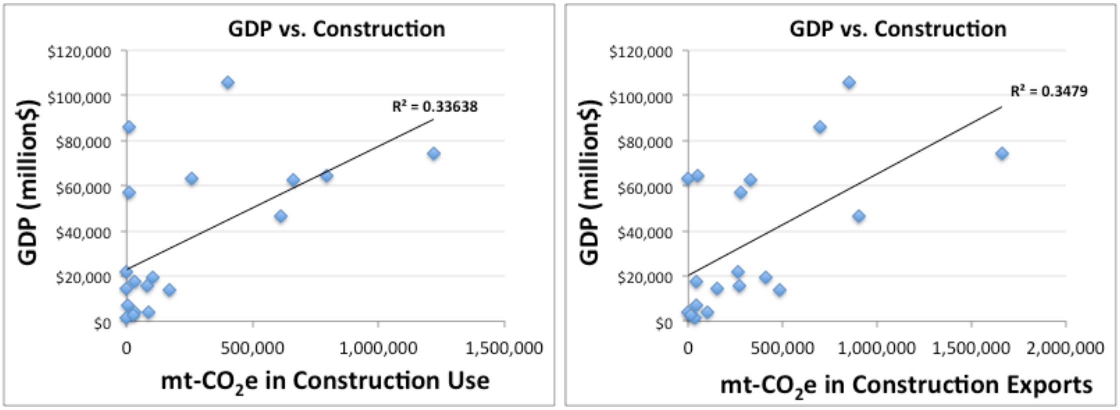


Figure S4-6h: Construction - GDP vs. GHGs from Use (left) and Export (right).

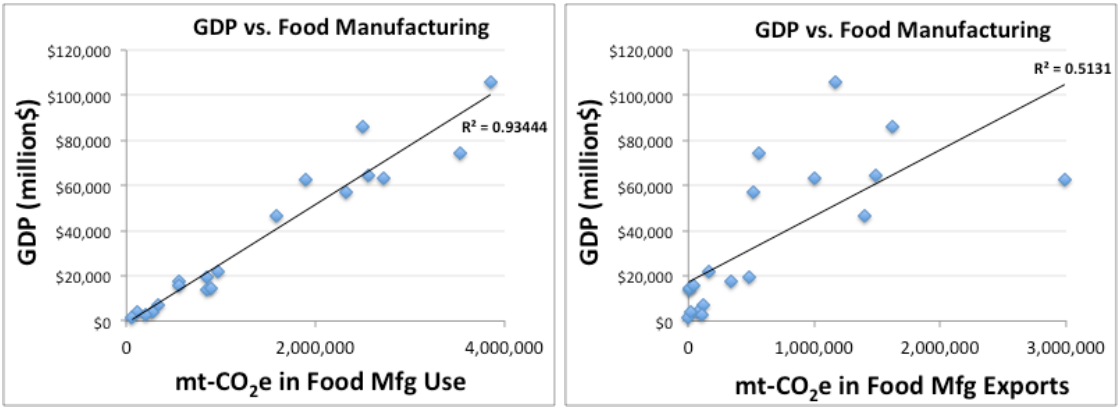


Figure S4-6i: Food Mfg. - GDP vs. GHGs from Use (left) and Export (right).

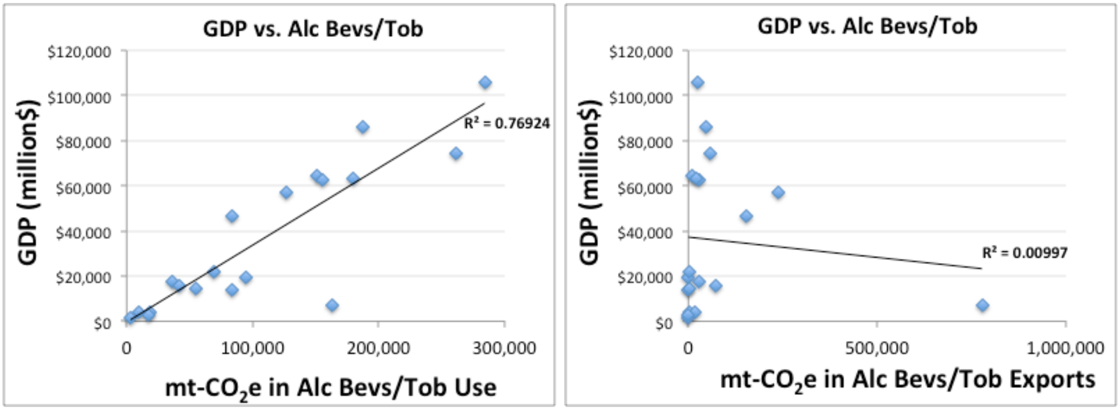


Figure S4-6j: Alc Bevs/Tob - GDP vs. GHGs from Use (left) and Export (right).

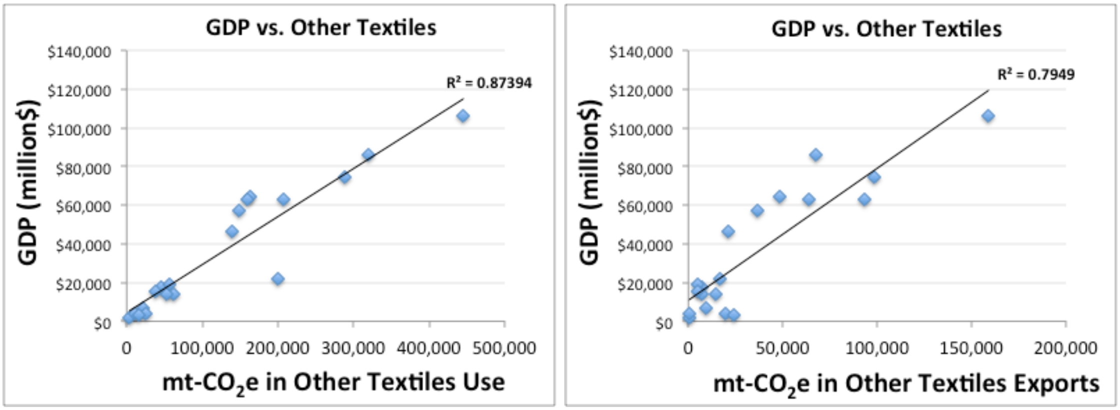


Figure S4-6k: Other Textiles - GDP vs. GHGs from Use (left) and Export (right).

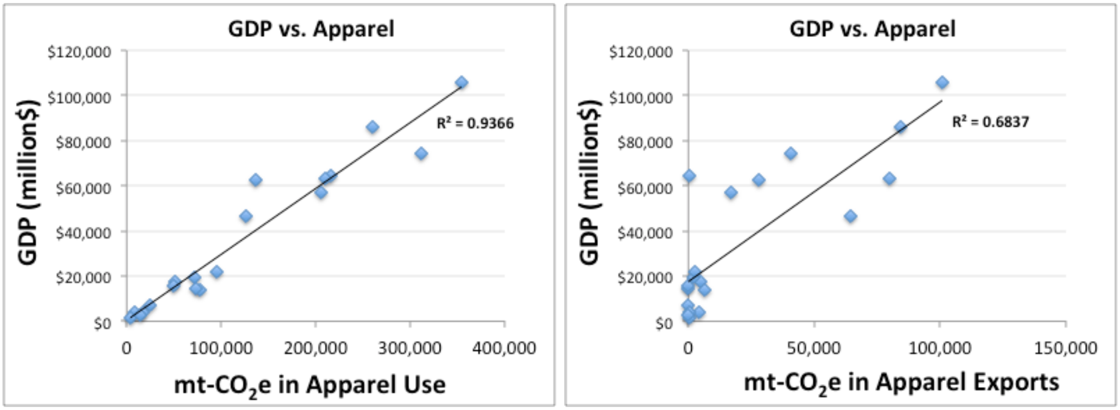


Figure S4-6l: Apparel - GDP vs. GHGs from Use (left) and Export (right).

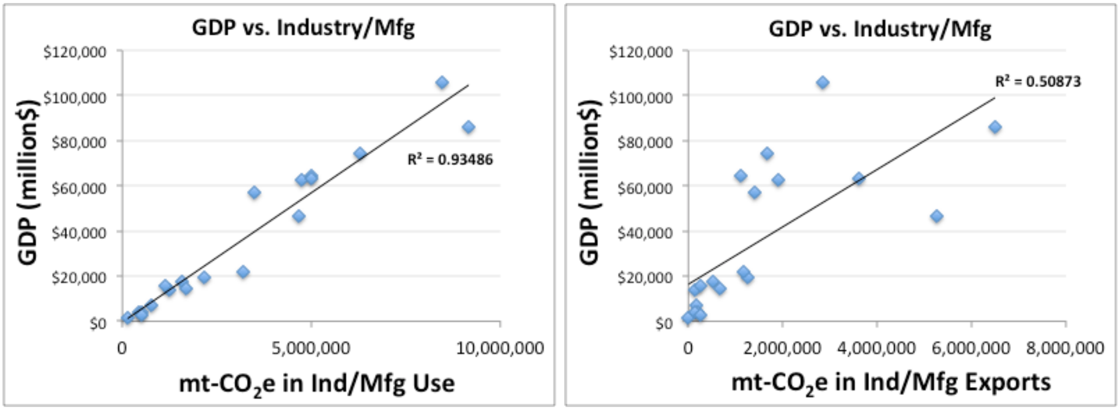


Figure S4-6m: Industry/Mfg. - GDP vs. GHGs from Use (left) and Export (right).

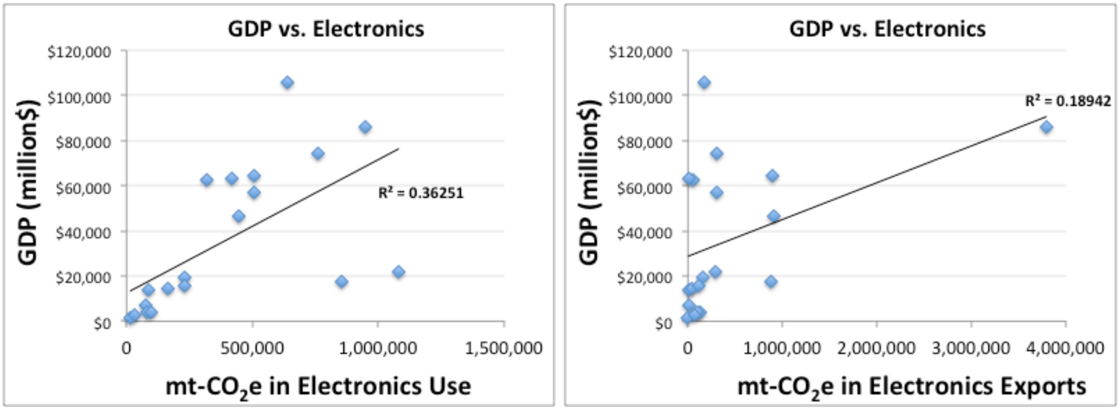


Figure S4-6n: Electronics - GDP vs. GHGs from Use (left) and Export (right).

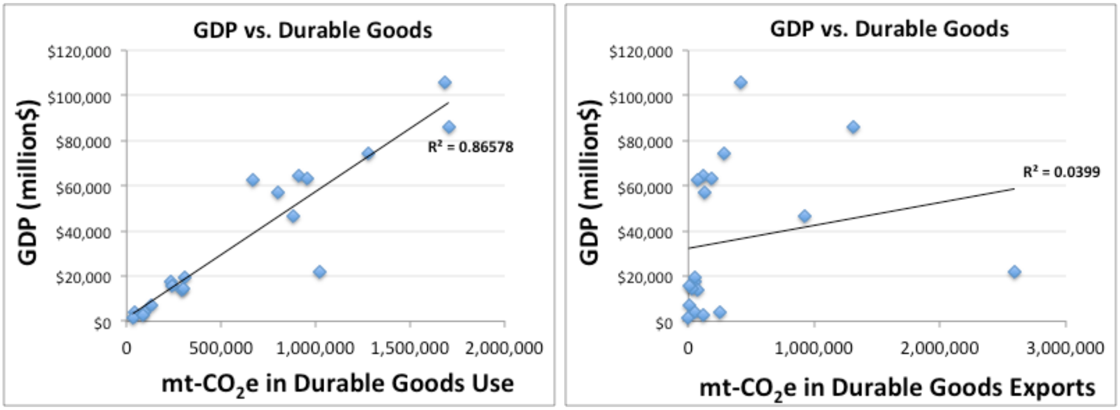


Figure S4-6o: Durable Goods - GDP vs. GHGs from Use (left) and Export (right).

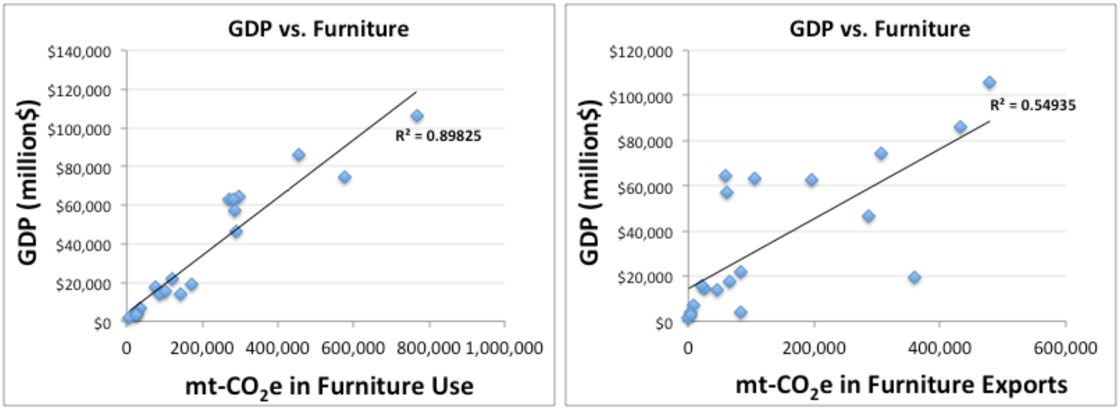


Figure S4-6p: Furniture - GDP vs. GHGs from Use (left) and Export (right).

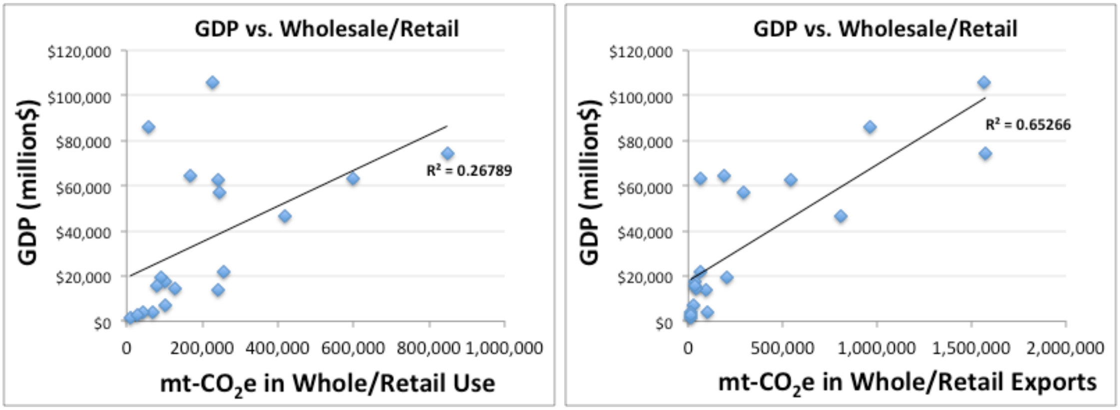
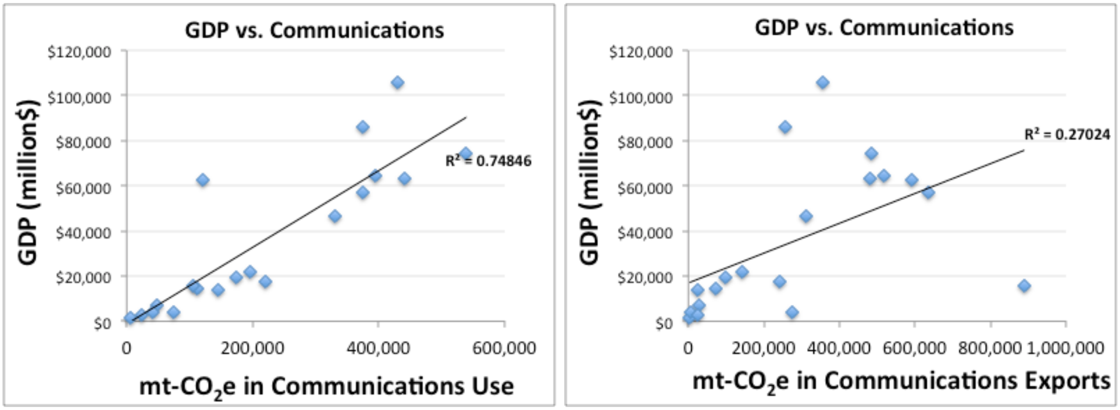


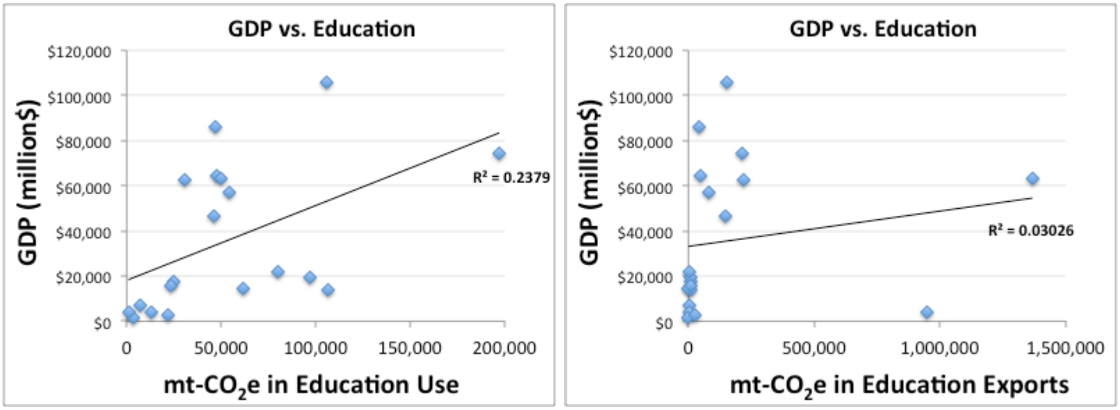
Figure S4-6q: Wholesale/Retail - GDP vs. GHGs from Use (left) and Export (right).



GDP vs. Communications

GDP vs. Communications

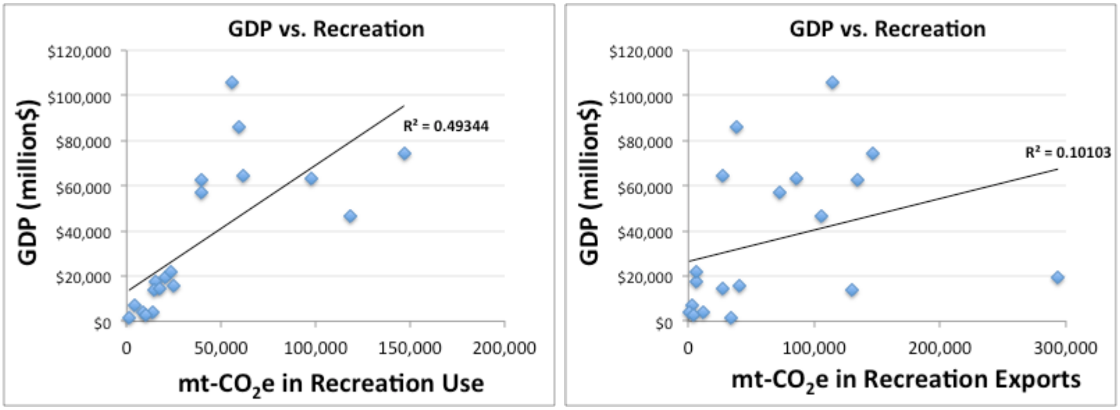
Figure S4-6r: Communications - GDP vs. GHGs from Use (left) and Export (right).



GDP vs. Education

GDP vs. Education

Figure S4-6s: Education - GDP vs. GHGs from Use (left) and Export (right).



GDP vs. Recreation

GDP vs. Recreation

Figure S4-6t: Recreation - GDP vs. GHGs from Use (left) and Export (right).

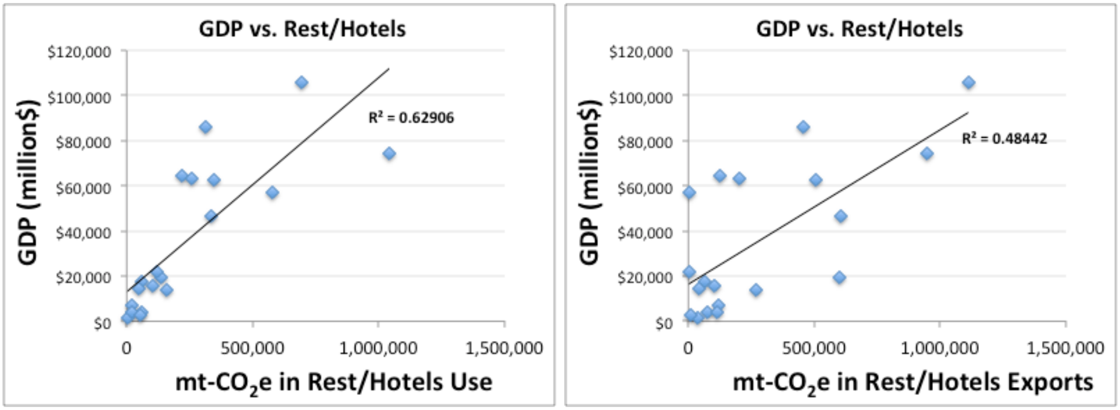


Figure S4-6u: Rest/Hotels - GDP vs. GHGs from Use (left) and Export (right).

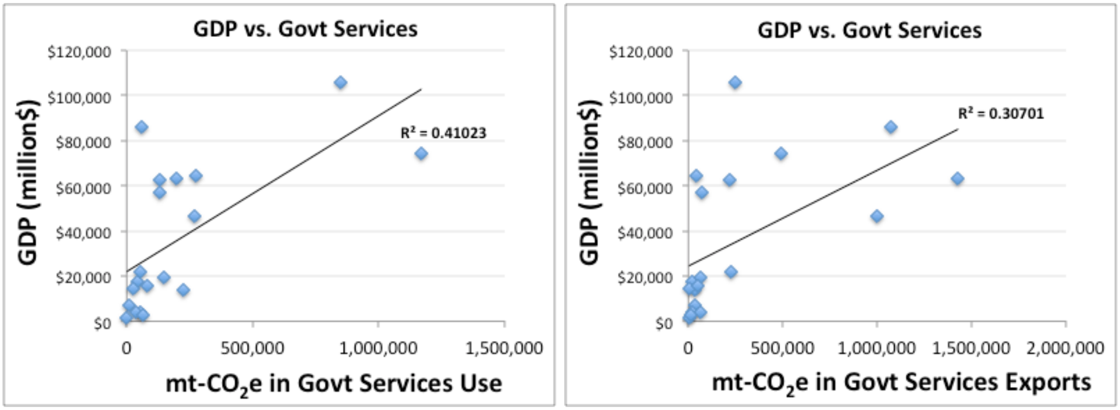


Figure S4-6v: Govt Services - GDP vs. GHGs from Use (left) and Export (right).

S 4-7 – Energy Use Benchmarks for 21 cities. Local and *[STATE]*.

	Commercial-Industrial		**Residential**		**Road Transport**
County	kWh/job/mo	therms/job/mo	kWh/HH/mo	therms/HH/mo	VMT/cap/day
Sacramento, CA	771 *[918]*	16 *[59]*	748 *[580]*	33 *[34]*	25.3 *[25.2]*
Napa, CA	719 *[918]*	16 *[59]*	714 *[1,071]*	25 *[24]*	26.0 *[25.2]*
Boulder, CO	1,156 *[1,214]*	39 *[94]*	852 *[743]*	56 *[58]*	24.2 *[28.2]*
Broomfield, CO	1,220 *[1,222]*	25 *[88]*	825 *[768]*	60 *[59]*	22.1 *[27.6]*
Denver, CO	948 *[1,222]*	46 *[88]*	546 *[768]*	47 *[59]*	25.3 *[27.6]*
Routt, CO	1,470 *[1,214]*	30 *[94]*	1,221 *[743]*	52 *[58]*	32.3 *[28.2]*
Collier, FL	1,300 *[1,187]*	5 *[13]*	1,780 *[1,354]*	1 *[2]*	32.3 *[30.9]*
Sarasota, FL	981 *[1,173]*	8 *[13]*	1,403 *[1,367]*	2 *[2]*	35.3 *[31.0]*
Broward, FL	1,188 *[1,187]*	4 *[13]*	1,352 *[1,354]*	1 *[2]*	28.5 *[30.9]*
Miami-Dade, FL	1,194 *[1,173]*	3 *[13]*	1,267 *[1,367]*	9 *[2]*	24.9 *[31.0]*
Washoe, NV	1,145 *[1,538]*	28 *[29]*	700 *[1,022]*	50 *[34]*	23.6 *[21.8]*
Tompkins, NY	799 *[892]*	42 *[37]*	564 *[554]*	33 *[46]*	19.5 *[18.9]*
Westchester, NY	666 *[966]*	29 *[37]*	589 *[575]*	51 *[47]*	28.3 *[19.7]*
Multnomah, OR	1,066 *[1,423]*	30 *[49]*	793 *[1,092]*	30 *[25]*	26.1 *[24.2]*
Philadelphia, PA	1,181 *[1,390]*	37 *[50]*	507 *[851]*	53 *[35]*	11.0 *[23.8]*
Roanoke, VA	1,202 *[1,495]*	42 *[33]*	1,261 *[1,247]*	54 *[23]*	28.9 *[29.1]*
Loudoun, VA	1,388 *[1,495]*	15 *[33]*	1,472 *[1,247]*	46 *[23]*	22.3 *[29.1]*
Snohomish, WA	1,200 *[1,513]*	30 *[36]*	994 *[1,114]*	27 *[25]*	22.5 *[24.3]*
Oregon METRO	1,212 *[1,425]*	34 *[49]*	714 *[1,071]*	25 *[24]*	23.9 *[26.4]*
NYC	772 *[892]*	26 *[37]*	374 *[554]*	37 *[46]*	8.4 *[18.9]*
DVRPC	1,203 *[1,279]*	46 *[52]*	842 *[851]*	48 *[50]*	21.7 *[23.7]*
US	1,450	70	982	36	27.0

State energy use data retrieved from (EIA, 2011); State employment statistics from (Census, 2011); State population and households from (Census, 2011); State VMT from (FHWA, 2008).

5. International Application

Community-wide greenhouse gas (GHG) accounting is confounded by the relatively small spatial size of cities compared to nations, due to which: energy use in essential infrastructures serving cities, e.g., commuter and airline transport, energy supply, water supply, wastewater infrastructures, etc., often occurs outside the boundary of the cities using them. A Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF) GHG emissions accounting method, tested in 8 US cities, incorporates supply-chain aspects of these trans-boundary infrastructures serving cities, and is akin to an expanded geographic GHG emissions inventory, covering Scopes 1+2+3. This chapter shows results from applying the TBIF in the rapidly developing city of Delhi, India.

The objectives of this research are to 1) describe data availability for implementing the TBIF within a rapidly industrializing country, using the case of Delhi, India, 2) identify methodological differences in implementation of the TBIF between Indian versus US cities, and 3) compare broad energy use metrics between Delhi and US cities, demonstrated by Denver, Colorado USA whose energy use characteristics and TBIF GHG emissions have previously been shown to be similar to US per capita averages.

This research concludes that most data required to implement the TBIF in Delhi are readily available, and the methodology could be translated from the US to Indian cities. Delhi's 2009 community-wide GHG emissions totaled 40.3 million mt-CO_2e, which are normalized to yield 2.3 mt-CO_2e/capita. Nationally, India reports its average per capita GHG emissions at 1.5 mt-CO_2e/capita. In-boundary GHG emissions contributed to 68% of Delhi's total, where end-use (including electricity) energy in residential buildings, commercial/industrial, and fuel used in surface transportation, contributed to 24%, 19%, and 21%, respectively. The remaining 4.3% in-boundary GHG emissions were from waste disposal, water/wastewater (WW) treatment, and cattle. Trans-boundary infrastructures were estimated to equal 32% of Delhi's TBIF GHG emissions, with 5% attributed to fuel processing, 3% to air travel, 10% to cement, and 14% to food production outside the city.

5.1 Introduction

Cities are increasingly recognizing their role in global greenhouse gas (GHG) emissions. Over one thousand cities have signed onto the ICLEI Cities for Climate Protection (CCP) – a framework for engaging local governments in political climate action commitments (ICLEI, 2009), and the Mexico City Pact (MCP) – an agreement by more than 140 world mayors to establish GHG emissions inventories and mitigation plans (WMSC, 2010). Outcomes from these efforts include public domain items such as the carbonn® Cities Climate Registry (cCCR) – a voluntary online tool where cities are reporting on their GHG inventories and mitigation commitments (cCCR, 2010). However to date, these tools while very valuable have not incorporated trans-boundary GHG emissions associated with human activities in cities which have been shown to be quite significant (Hillman & Ramaswami, 2010; Kennedy, et al., 2009; Ramaswami, et al., 2008).

Understanding GHG emissions associated with cities in India, China, and US is important due to their contribution to world totals. A report by the International Energy Agency (IEA) notes that India, China, and US together, constitute 42% of the world's population, and 46% of the world's CO_2 from fuel combustion (IEA, 2010). Moreover, in India, China, and US, 30%, 44%, and 82% of people live in urban areas, respectively (TWB, 2010). With rapid urbanization seen especially in Indian and Chinese cities, quantification of GHG emissions associated with cities becomes important. GHG emissions accounting for cities however, is confounded by the relatively small spatial size of cities compared to nations, due to which:

- Essential infrastructures - commuter and airline transport, energy supply, water supply, wastewater infrastructures, etc. - cross city boundaries, hence energy use to provide these services often occurs outside the boundary of the cities using them (Hillman & Ramaswami, 2010; Ramaswami, et al., 2008).
- Significant trade of other goods and services also occurs across cities, with associated embodied GHGs.

Two approaches to GHG emissions footprinting (see review in (Chavez & Ramaswami, 2011; Ramaswami, et al., 2011)) can be used to alleviate these challenges. The two approaches are the Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF), and the Consumption-Based Footprint (CBF).

TBIF utilizes the concept of scopes from corporate GHG emissions accounting protocols to include both in-boundary and trans-boundary GHG emissions associated with city activities; hence it has also been referred to as an expanded geographic inventory. TBIF recognizes that cities include both producers and consumers, and focuses on infrastructure supply-chains that serve the entire community as a whole. The GHG emissions accounted for by the TBIF are a) direct in-boundary (Scope 1), b) indirect GHG emissions from generation of purchased electricity (Scope 2), and c) GHG emissions from trans-boundary infrastructures serving cities (Scope 3), such as water supply, transportation fuels, airline and commuter travel, and other critical supply chains. Inclusion of trans-boundary infrastructures (Scope 3) warrants careful allocation of GHG to avoid double counting (Ramaswami, et al., 2008). For example, infrastructures such as large electric power plants, or oil refineries are easily recognized within city boundaries, and their GHG can be readily allocated based on local demand, thus reducing double counting. TBIF considers the community as a whole, maintaining residential, commercial, and industrial activities together, consistent with the geopolitical definition. Although TBIF captures life-cycle GHGs from essential infrastructures serving cities, it does not account for life-cycle GHGs of other, non-infrastructure goods/services *consumed* by households, or other non-infrastructure supply-chains serving local industries because such data are often proprietary. Indeed, incorporating key industrial supply-chains to the TBIF can enhance this method because TBIF includes both consumers and producers in cities. Improved blended metrics that combine GHG/capita and GHG/productivity may be needed.

The second approach is a consumption-based footprint (CBF), which quantifies the full life-cycle GHG emissions from economic final consumption in a city defined as household expenditures, government expenditures, and business capital investments. CBF have traditionally been conducted at the scale of households, using household consumer expenditure surveys (CES) (Jones & Kammen, 2011), with regional/national production matrices, coupled with sector specific GHG emission intensities (e.g., Lenzen

& Peters 2010). Recent efforts have been made to compute city-scale CBF using final consumption vectors reported in sub-national input-output (IO) tables (Stanton, et al., 2011). While CBF incorporates all trans-boundary GHG relating to local household consumption, local production of exports is allocated out. Such allocation alters the definition of a community, where the geopolitical unit is split in two: local final consumption sectors, and local producers who export goods elsewhere.

Both approaches have their advantages and disadvantages, and neither is complete, in that neither fully accounts for all life-cycle supply-chains serving both producers and consumers in cities. TBIF accounts for life-cycle GHGs of essential infrastructures serving cities, but does not account for life-cycle GHGs of all other, non-infrastructure goods/services consumed by households or those used in industrial production. Also, TBIF recognizes that both, city's production and consumption activities are intrinsically linked, and focuses on publicly managed cross-scale infrastructures such as commuter travel, airline travel, freight, and energy & water supply-chains that transcend city boundaries and serve the entire community as a whole. In contrast, CBF ignores the in-boundary and supply-chain impacts of commercial-industrial activities that are exported, focusing only on consumption and its supply-chains.

The utility of TBIF has been described in Ramaswami et al. (2011). In summary, TBIF can be used to quantify a community's GHG emissions by addressing direct energy use and also embodied energy in infrastructures. The method keeps a community's energy use together (residential and business activity), quantifying community GHG emissions as a whole. The method can link in-boundary energy use and GHG emissions, to local air pollution and local health impacts, and is able to track the effects stemming from infrastructure policies across-scale address buildings energy supply, transportation, water/WW, and waste. By its trans-boundary inclusions, TBIF addresses regional cross-sector and cross-scale infrastructure efficiencies, such as mass-transit, or expanded tele-presence aimed at reducing air travel. Lastly, supply-chain vulnerabilities impacting local economies as a whole are addressed.

ICLEI-USA has gathered a group of technical leaders from business, government, and academia to develop a draft *community-scale GHG emissions accounting and reporting* *protocol* (ICLEI, 2011). The protocol recognizes and seeks to address the need for standardized GHG emissions accounting of cities. Four reporting approaches are defined in the draft protocol framework – Basic, Expanded, Local Government Focus Area, and Consumption-Based. Both, the *Basic Reporting Standard (Basic)* and *Expanded Community Impact Reporting (Expanded)* are derived from TBIF. See Table 5-1 for a full description of Basic and Expanded reporting standards.

The main objective of this chapter is to evaluate the TBIF using Delhi, India as the case study. More specifically, this chapter 1) describes data availability for implementing the TBIF within Delhi, a rapidly industrializing city, 2) identifies methodological differences between the implementation of TBIF in Indian versus US cities, and 3) compares broad energy use metrics between Delhi and US cities, demonstrated by Denver whose TBIF per capita has been shown to be similar to US averages.

Table 5-1: Basic and Expanded reporting frameworks for ICLEI-USA community-scale GHG emissions accounting and reporting protocol.

Methodology	Use in ICLEI-USA Draft Protocol	
Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF) *(Ramaswami et al., 2008; Hillman & Ramaswami, 2010; Kennedy et al., 2010; Ramaswami et al., 2011)*	Basic GHG Emissions Reporting Standard	**In-Boundary Contributions. GHG Emissions from:** • Combustion of stationary sources (natural gas, LPG, Fuel Oil, etc.) • Combustion of mobile sources (gasoline, diesel) • Power plant emissions for electricity used in community • Landfilling of waste generated in community • Other industrial processes (e.g. calcination) **Suggested Trans-Boundary Contributions:** • GHG emissions associated with production of fuels used in community, including inputs to electric power plants*
	Expanded GHG Emissions Reporting Standard	• As in Basic Reporting shown above, PLUS… **Suggested Trans-Boundary Contributions:** • Origin-Destination or one-way allocation of transportation (road, air, freight, maritime) • Embodied emissions from trans-boundary water pumping and water/WW treatment* • Embodied emissions from food production* • Embodied emissions from cement production*

** Assumed that in most cities, these activities occur outside of city boundary, hence trans-boundary.*

5.2 Trans-Boundary Infrastructure Footprint (TBIF) Method

Description and Data Needs

The TBIF accounts for in-boundary GHG emissions from buildings (residential, commercial, and industrial), road transportation, industrial processes (i.e. waste emissions, calcination), plus embodied GHG emissions of a city's trans-boundary infrastructure supply-chains, e.g., electricity supply, fuel production, water/WW treatment, cement production, spatially allocated airline and freight transport, and production of food consumed in the city, see Table 5-1. The method has been tested in the US (e.g., Ramaswami et al. 2008; Hillman & Ramaswami 2010), yielding a convergence in per resident GHG emissions from city to national scale for a set of seven larger US cities, suggesting the inclusion of these selected trans-boundary infrastructures generate scale consistency from city to national levels. Table 5-2 illustrates energy and material uses accounted for by the TBIF, along with appropriate benchmarks, and associated emission factors (EF). Table 5-3 illustrates the data needs for benchmarking energy and material use described by the TBIF.

Table 5-2: TBIF energy & materials use benchmarks, and EFs.

Activity Sector	In-Boundary Energy & Materials Use	In-Boundary Energy & Materials Use Benchmark	Associated EF In- & Trans-Boundary *
Buildings Energy Use & Industrial Process Emissions – Residential, Commercial, Industrial, Government, and industrial processes (e.g. waste, calcination)	Energy Use (residential, commercial, industrial, government): - Electricity - Natural Gas - Cooking Fuels (e.g. LPG) - Heating Fuels (e.g. Fuel Oil, Propane) Industrial process emissions: - Waste (methane generation) - Other (industrial emissions)	Residential Intensity: • kWh/HH/mo • m^3/HH/mo • liter-CF/HH/mo • liter-HF/HH/mo • Total kBTU/HH/mo Commercial Intensity: • kWh/sm_c/yr • Other stationary fuels kBTU/sm_c/yr • Total kBTU/sm_c/yr Industrial Process: • mt of waste/capita/yr	In-Boundary EF associated with fuel combustion: EF_{Elec} = kg-CO_2e/kWh EF_{NG} = kg-CO_2e/ m^3 $EF_{Cooking\ Fuels}$ = kg-CO_2e/liter $EF_{Heating\ Fuels}$ = kg-CO_2e/liter EF_{Waste} = kg-CO_2e/mt-waste Trans-Boundary EF associated with fuel production: $EF_{Coal}^{Prod,LCA}$ = kg-CO_2e/mt-coal $EF_{NG}^{Prod,LCA}$ = kg-CO_2e/m^3 $EF_{CookingFuels}^{Prod,LCA}$ = kg-CO_2e/liter $EF_{HeatingFuels}^{Prod,LCA}$ = kg-CO_2e/liter

Table 5.2 (cont.)

Transportation Energy Use – Road, Air Travel, Freight, and Rail	Energy Use: - Gasoline, Diesel, and CNG use in road transport - Jet Fuel use in air travel - Fuel (i.e. Diesel) use in freight transport - Diesel use in rail transport	Surface Travel Intensity: • VKT/capita/day • Fleet Fuel Efficiency (VKT/liter of fuel) Air Travel: • liter of jet fuel/enplaned passenger Rail: • Total Person Kilometers Traveled (PKT) • PKT/cap/day • Total BTU	In-Boundary EF associated with fuel combustion: $EF_{Gasoline}$ = kg-CO_2e/liter EF_{Diesel} = kg-CO_2e/liter $EF_{Jet\ Fuel}$ = kg-CO_2e/liter EF_{Rail} = kg-CO_2e/liter Trans-Boundary EF associated with fuel production: $EF^{Prod,LCA}_{Gasoline}$ = kg-CO_2e/liter $EF^{Prod,LCA}_{Diesel}$ = kg-CO_2e/liter $EF^{Prod,LCA}_{JetFuel}$ = kg-CO_2e/liter
Materials Use – Water, Food, Cement	- Use of water, food, and cement.	Water: • treated wastewater (WW) liters/capita • pumped water liters/capita Food: • mt-food/HH Cement: • mt-cement/capita	In-Boundary EF associated with materials: Logic Rules Applied Accordingly [#] Trans-Boundary EF associated with materials production: EF_{WW} = mt-CO_2e/volume-treated WW EF_{water} = mt-CO_2e/volume-pumped water EF_{food} = mt-CO_2e/mt-food EF_{cement} = mt-CO_2e/mt-cement
City-Wide	• Total local population *(capita)* • Total city area *(sq-km)* • Population Density *(capita/sq-km)* • Total homes *(HH)*	• People per home *(capita/HH)* • Residential floor area (sm_r/HH) • Total commercial floor area (sm_c)	• Total floor area per capita (sm/cap) • City GDP • Emission intensity per unit GDP *(GHG/GDP)* • Emission intensity per resident *(GDP/cap)* • Number of jobs

* Cities are unique in that most have these trans-boundary GHG emissions occurring outside of the community. As in-boundary data of these activities become available, the energy use and GHG emissions should be updated accordingly.

[#] These large infrastructures are mostly absent in US cities. GHG from infrastructures allocated based on local demand, and are allocated out to avoid double counting.

VKT = Vehicle Kilometer Traveled. sm_r = residential square meters. sm_c = commercial square meters. sm = total square meters. HH = Households. GDP = Gross Domestic Product.

Table 5-3: Data needs for benchmarking the TBIF to represent energy & materials use.

Activity Sector	Data Needs
Buildings Energy Use & Industrial Process emissions	• Total residential floor area *(sm_r)* • Total Commercial floor area *(million sm_c)* • Total floor area per capita *(sm/capita)* • Residential Electricity, Natural Gas, Cooking Fuels, and Heating Fuels use • Commercial-Industrial-Government Electricity, Natural Gas, Other fuel use • Total waste generated in city
Transportation Energy Use	• Allocated daily VKT *(VKT/cap/day)* • Fleet fuel efficiency • Volume of Gasoline, Diesel, and CNG used in road transport • Number of enplaned passengers at regional airport (Domestic, International) • Jet Fuel liters loaded into airplanes • % of planes fueling at airport • Tons of Long Distance Freight, and liters of fuel per ton moved • Energy used in Rail transport
Materials Use	• Volume of water used (i.e. pumped) • Energy used in pumping water • Volume of wastewater treated • Energy used in WW treatment • % of water used for Residential, Commercial, and Industrial uses • Food consumed/used in the community • Cement use in the community

5.3 Socio-Economic Profile and Overview of Energy Use & GHGs for Delhi, India

India's national population is estimated at 1,155 million people (TWB, 2010), corresponding to about 17% of the world's population. India's GDP is $3,275 billion, roughly 3% of the world's GDP (TWB, 2010), and total primary energy use is estimated at 20 Quad BTU (EIA, 2010), about 4% of the world's total primary energy use. India's annual growth in primary energy use and GDP are 7% and 8.2%, respectively, relative to trends for the US of 0.3% and 2.3%, respectively. In Delhi, even greater GDP growth is projected, with annual GDP growth reported at 15.9% (DES, 2009).

Delhi is a city-state and the capital of India. Home to almost 18 million people, it boasts a vibrant economy which is poised for continued growth. Spurred by an influx of jobs in IT, telecommunication, banking, and manufacturing, Delhi has become an attractive place for many, generating a per resident GDP that is about twice that of India's ($6,037 vs. $2,835 PPP US$-2009), see Table 5-4. The Delhi government is also initiating a wide range of sustainable infrastructure programs addressing energy use and GHG emissions. Two such examples are the new more stringent building codes (Energy Conservation Building Code (ECBC) implemented in 2009, (DDE, 2009)), and fuel switching of all commercial fleets from gasoline/diesel to natural gas (Indian Supreme Court legislation in 1998, (Mehta, 2001)), both of which can help reduce carbon emissions per GDP.

Previous research has contributed to some level of energy use and GHG emissions accounting for Delhi. The earliest known GHG emissions research in Delhi was conducted for the baseline year of 1995 by Sharma et al. (2002a-d). That research evaluated GHG emissions from use of electricity, natural gas, LPG, kerosene, gasoline, and diesel, plus the embodied emissions associated with the production of cement, steel, rice, and milk used in Delhi (Sharma et al. 2002a-d). A more recent study inventoried Delhi's 2007 GHG emissions from in-boundary activities only (Ghosh, 2009).

Table 5-4: Comparisons of key demographic and economic variables in USA, India, and Delhi.

2009	**U.S.**	**India**	**Delhi**
Population (million) [a]	307	1,155	17.6
Annual % change	0.93%	1.4%	2.9%
% Urban [a]	80.8%	29.8%	93.2%
% Rural [a]	19.2%	70.2%	6.8%
GDP (billion USD-Real); ***{billion USD-PPP}*** [b]	$14,119	($1,310); *{$3,275}*	($42.5); *{$106}*
Annual % change	2.3%	8.2%	15.9%
GDP/capita (USD-Real/cap); ***{USD-PPP/cap}***	$45,989	($1,134); *{$2,835}*	($2,415); *{$6,037}*
Annual % change	1.4%	8.3%	12.6%
Income/capita (USD/cap) [c]	$40,947	$833	$1,965
GHG/capita (mt-CO_2e/cap) [d]	21.6	1.5	2.4
GHG/GDP (mt-CO_2e/mill $GDP) [d, *]	482	1,317	948
Primary Energy (EJ) [e]	104	21	0.53
Annual % change	0.3%	7%	

a. Population statistics sources: U.S. and India = The World Bank (2010); Delhi = DCO (2009).
b. Gross Domestic Product sources: U.S. and India = The World Bank (2010); Delhi = DES (2009).
c. Per capita income sources: U.S. = BEA (2009); India/Delhi = CSO (2009).
d. Sources for GHG estimates: U.S. = EPA (2011); India = MEF (2010); Delhi = Estimated in this study.
e. Primary Energy: U.S. and India = International Energy Agency; Delhi = estimated.
*. GDP in Real U.S. Dollars (USD).

5.4 Data Sources and Results

Indian energy-use data are more readily available at the state-level versus the city-level. Because Delhi is a city-state, i.e. considered a union territory among six others in India, energy-use data was readily available, which may not be the case for other Indian cities. This section first introduces important demographic trends in Delhi. Then, required data sources and their availability for completing the TBIF in Delhi are discussed, with results presented for demographics and then the activity sector categories presented above in Table 5-2 and Table 5-3: 1) Building Energy Use & Industrial Processes, 2) Transportation Energy Use, and 3) Materials Use.

5.4.1 Delhi Statistical Handbook

A fair amount of the socio-demographic and in-boundary energy use data for Delhi was obtained through the Delhi Statistical Handbook (DSH), published by the Directorate of Economics & Statistics of the Delhi Government (DES, 2010). Data reported in the DSH ranges from various economic, demographic, and health parameters, to electricity used in Delhi. The edition of the DSH used in this thesis is number 35, and as in all previous issues, the DSH depends on primary data supplied by various agencies/ministries, thus serving as a conduit for large amounts of data relating specifically to the National Capital Territory (NCT) of Delhi. Socio-Demographic data retrieved from the DSH and used in this study is population, households, population density, employment, and GDP, all of which have been supplied by the Directorate of Census Operations (DCO, 2009). Energy use data retrieved from the DSH and used in this study is electricity, supplied by the Delhi Electricity Regulatory Commission (DERC, 2009), and the end-use of other fuels such as LPG and Kerosene, supplied by the Ministry of Petroleum and Natural Gas (MPNG, 2009). Cattle head counts have also been retrieved from the DSH, and supplied by the Directorate of Animal Husbandry (DAH, 2010).

Methodological details pertaining to data collection from the respective ministries have proven to be sparse and difficult to obtain. For example, it is unknown whether energy use data reported through the DSH has been collected through utility sales and revenue shares, or whether it has been estimated through surveys representing average use among sector-wise users.

5.4.2 Demographics

Population data for Delhi was obtained from the Directorate of Census Operations (DCO) through the DSH (DCO, 2009), which reports Delhi's 2009 population equal to 17.6 million people. Household counts in Delhi were last reported by DCO in 2001. Thus, using home occupancy as reported in 2001 (4.6 people/HH), we estimated Delhi's homes corresponded with 3.8 million homes. Two estimates of population density were obtained; the first was a 2001 (DCO, 2009) estimate, equal to 9,340 people/sq-km, and the second was a 2007 estimate equal to 11,463 people/sq-km (UN, 2010).

Delhi employment statistics, which were last reported for 2001 (DCO, 2009), illustrate the annualized employment growth from 1981-1991 and 1991-2001 are almost identical, equal to 5% per annum. Applying the assumption of constant employment growth from 2001-2008 yielded an estimated 6.8 million jobs in Delhi, in 2009.

Floor areas for residential, commercial, and industrial units in Delhi were not locally available. A literature search yielded national estimates of average urban residential floor areas equal to 46.8 sq-meter/HH (TOI, 2008), and an aggregate India commercial floor area was reported equal to 516 million sq-meter (Satish Kumar, Kapoor, Deshmukh, Kamath, & Manu, 2010). While assuming that commercial activity occurs in urbanized places, commercial floor areas were apportioned to Delhi by urbanized population, resulting in an estimate for Delhi equal to 25.7 million sq-meter. Industrial floor space is typically difficult to quantify in any community, and was unattainable in Delhi.

5.4.3 Buildings Energy Use and Industrial Process Emissions

Sector-wise electricity use in 2009 was reported by DERC (DERC, 2009). Unlike the US where natural gas is a dominant energy carrier second to electricity, building electricity use in Delhi is followed by a series of other fuels that serve end-use needs of the community including liquid petroleum gas (LPG), kerosene, and compressed natural gas (CNG). Use of these other fuels were obtained from the Ministry of Petroleum and Natural Gas (MPNG, 2009), and apportioned to end-use sectors using ratios previously estimated for Delhi (Ghosh, 2009) (e.g., LPG: 95.9%-Residential, 3.5%-Commercial, 0.6%-Industrial).

5.4.3.1 Residential Energy Use Benchmarks

Several factors have been shown to contribute to household energy use in India, some of which include home size, home construction material, income, and climatic/weather conditions (Pachauri, 2004; Pachauri & Jiang, 2008). Pachauri (2004) notes that on average, direct energy use of urban Indian households is two-to-three times greater than rural households.

Electricity use was the dominant end-use energy source for Delhi households in 2009, and its monthly use by households is estimated to have been 191 kWh/HH/month (DERC, 2009). Nationally, Indian households use 48 kWh/HH/month (IEA, 2008a). This difference in average household electricity use between Delhi and India is in line with Sharma et al. (2002a) who estimated Indian urban electricity use to be is about three times higher than national averages.

Delhi households typically do not use natural gas or other fuels (e.g., propane) for space heating as is done in the US, but do use LPG and kerosene for cooking; any coal or biomass use for cooking was not reported in this research. The estimated monthly use of each of the two fuels are LPG = 25.3 liters/HH and Kerosene = 3.4 liters/HH (MPNG, 2009). This compares to 7.8 liters/HH and 4.2 liters/HH, respectively, with national statistics (IEA, 2008a). Combining these end-uses of energy yields an energy end-use intensity (EUI) of Delhi residences, estimated at 1,489 MJ/HH/mo. India's household EUI is reported at 273 MJ/HH/mo (IEA, 2008a). These estimates roughly conform to estimates by Pachauri (2004) who notes that urban household energy use is at least triple that of national averages.

5.4.3.2 Commercial Energy Use Benchmarks

Commercial buildings energy use consisted of electricity, LPG, CNG, and diesel. Electricity use, excluding use in treating/pumping water and wastewater, was equal to 5,795 million kWh (DERC, 2009), or 225 kWh/sm_c/yr using estimated commercial floor areas from national reports. Nationally, (Gupta, 2011) estimates average commercial electricity use intensity equals 189 kWh/sm_c/yr, while estimates provided by (IEA, 2010) reports 93.6 kWh/sm_c/yr for India.

Total end-use of the other fuels in commercial buildings are: LPG = 43 million liters, CNG = 30.6 million cubic meters, and Diesel = 15.8 million liters (MPNG, 2009). Combining these energy end-uses yields a EUI for Delhi's commercial buildings equal to 923.8 MJ/sm_c/yr.

5.4.3.3 Industrial Energy Use Benchmarks

Energy statistics report industries in Delhi used 2,991 million kWh in 2009 (DERC, 2009). Other energy end-uses by Delhi industries are LPG = 6.9 million liters, CNG = 46.4 million cubic meters, High Speed Diesel (HSD) = 5.9 million liters, Light Diesel Oil (LDO) = 2.1 million liters, and Diesel = 3 million liters (MPNG, 2009).

5.4.3.4 Industrial Process Benchmarks

The Delhi Pollution Control Committee (DPCC) estimates Delhi generates 7,310 tonnes of municipal solid waste (MSW) daily (DPCC, 2010), amounting to about 0.16 tonnes/resident/yr, which compares to 0.14 tonnes/resident/yr nationally (Sharholy, Ahmad, Mahmood, & Trivedi, 2008). About 7% of Delhi's waste is diverted in the form of compost. Additionally, there are three on-going waste-to-energy projects in Delhi that promise to divert close to 15% of today's MSW (DPCC, 2010).

Releases of untreated wastewater can also be a source of considerable GHG emissions. Rivers, lakes, lagoons, etc., provide anaerobic conditions for untreated wastewater, resulting in methane (CH_4) and nitrous oxide (N_2O) production. It is estimated that Delhi captures and treats 63% of its total produced wastewater (MUD, 2010). Noting that Delhi treated 1,584 million liters of wastewater per day in 2009 (MUD, 2010), we estimate the 2009 releases of untreated wastewater total 339,633 million liters.

Among the other industrial processes recognized by the IPCC as contributors to GHG emissions, cement production is the most prominent (IPCC, 2006a). The Cement Manufacturers Association (CMA) reports no cement production within the boundaries of Delhi, thus providing a basis for incorporating cement as a relevant Scope 3 item. No other industrial process emissions were readily identified within Delhi boundaries.

5.4.3.5 Emissions Factors

Electricity EF

Electricity is generated in Delhi at five power plants; three coal-powered and two natural gas powered power plants. Their EF, in kg-CO_2e/kWh are 1.16, 1.52, 1.39, 0.59, 0.36, respectively (Ghosh, 2009). Nationally, India has two power grids. The first grid is the Integrated Northern, Eastern, Western, and North-Eastern (NEWNE), which has an EF equal to 0.83 kg-CO_2e/kWh. The second is the Southern grid, whose EF is equal to 0.76 kg-CO_2e/kWh. This results in a blended national electricity EF equal to 0.82 kg-CO_2e/kWh (CEA, 2009), previously reported to consist of 90% coal, with the remining 10% being natural gas, oil, and wind (MEF, 2010). The national electricity EF includes transmission and distribution (T&D) losses (including unauthorized connections), which have been estimated to equal about 24% across India (TWB, 2010). Because the NEWNE regional grid serves Delhi, its electricity EF was used upon the recommendation of ICLEI-SA.

Fuel EF – Production and Combustion

The combustion EFs of fuels used in buildings were obtained from the 2007 national India inventory (MEF, 2010), and are consistent with IPCC 2006. The EF for fuel combustion are: NG = 2.15 kg-CO_2e/cubic meter, LPG = 1.68 kg-CO_2e/liter, and kerosene = 2.7 kg-CO_2e/liter. Production EF of LPG and kerosene were adopted from (Lewis, 1997) since no India-specific data was identified. Those production EFs are reported as: LPG = 0.26 kg-CO_2e/liter, and kerosene = 0.22 kg-CO_2e/liter.

MSW EF

EF from waste landfilling is estimated using IPCC's default methodology (IPCC, 2006b):

$$CH_4 = MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times \left(\frac{16}{12} - R\right) \times (1 - OX)$$

Equation 5-1

where MSW_T is the total waste generated, MSW_F is the fraction sent to landfills, MCF is the methane correction factor, DOC is the degradable organic carbon, DOC_F is the fraction of DOC dissimilated, F is the fraction of CH_4 in landfill gas with a default value of 0.5, R is the recovery of CH_4, and OX is the oxidation factor with a default value of 0. For the variables requiring specific data relating to Delhi's waste composition, namely MCF, DOC, and DOC_F, we turn to the literature. Both (Sharma, Dasgupta, & Mitra, 2002b) and (S Kumar, Mondal, Gaikwad, Devotta, & Singh, 2004) estimate MCF and DOC at 0.4 and 0.15, respectively. However their estimates of DOC_F differ, where (Sharma, et al., 2002b) report 0.5, and (S Kumar, et al., 2004) report 0.77. Upon substituting these variables into Equation 5-1, we estimate the range of Delhi's EF from landfilling as 0.4 to 0.6, kg-CO_2e/kg-$\text{waste}_{\text{landfilled}}$, and used the average of the two.

CH_4 and N_2O from released WW

EF relating to Methane (CH_4) and Nitrous Oxide (N_2O) production from released untreated wastewater is consistent with IPCC methodology. The EF for describing the methane production is:

$$EF_{RiverineCH_4} = C_{influent-COD} \times B_0 \times MCF \times GWP_{CH_4}$$

Equation 5-2

where, $C_{influent\text{-}COD}$ is the concentration of chemical oxygen demand (COD) in the influent treated wastewater, which for Delhi has been estimated from (DPCC, 2010) as an average of all Delhi treatment plants, equal to 407 kg-COD/million-liter. B_o is the maximum CH_4 producing capacity, and its default value is 0.25 kg-CH_4/kg-COD. *MCF* is the methane correction factor for rivers and lakes, and its default value is 0.1. GWP_{CH4} is the methane global warming potential (GWP), equal to 24 kg-CO_2e/kg-CH_4. Multiplying the four terms yields 244 kg-CO_2e/million-liter of methane from Delhi's untreated released wastewater.

The EF for nitrous oxide from untreated wastewater releases is adapted from a PNAS study by (Beaulieu et al., 2011), and is written as:

$$EF_{RiverineN_2O} = C_{influentN_2O} \times EF_{Den,N_2O} \times GWP_{N_2O} \qquad \textbf{Equation 5-3}$$

where, $C_{influentN2O}$ is the concentration of inorganic nitrogen in the influent wastewater, and because Delhi specific data was not available, we assumed the concentration equal's that of another Indian city, Hyderabad, which has been estimated as 52 kg-N/million-liter (Miller, 2011). $EF_{Den,N2O}$ is the default value of N_2O emissions from nitrification and denitrification in rivers, 0.005 kg-N_2O/kg-N (IPCC 2006). GWP_{N2O} is the nitrous oxide GWP, equal to 298 kg-CO_2e/kg-N_2O. Multiplying the three terms yields 77 kg-CO_2e/million-liter of nitrous oxide from Delhi's untreated released wastewater.

5.4.4 Transportation Energy Use

5.4.4.1 Surface Travel Benchmarks

Estimating energy use and GHG emissions from road transport can be challenging in US cities due to the trans-boundary movement of vehicles across multiple cities in a commuter-shed. For example, in the Denver region consisting of 10 cities (including Denver), 59% of workers commute into Denver, and 33% of Denver residents travel outside for work (DRCOG, 2007). In this study, because Delhi is a mega city, we can assume the administrative boundaries of Delhi and the commuter-shed overlap, which significantly simplifies the analysis. The assumption was confirmed by finding that only 3% of Delhi's VKT are trans-boundary, see below. The latest estimates of Delhi's in-boundary VKT were obtained from the Central Road Research Institute (CRRI), and are reported at 151 million daily VKT for 2009 (CRRI, 2009), yielding 8.8 VKT/resident/day. The CRRI study also estimated daily vehicle counts entering and leaving Delhi as 431,246 (inbound), and 464,183 (outbound). To estimate the proportion of VKT associated with trans-boundary traffic, the average Delhi vehicle trip length, estimated to be 10 km (IDFC, 2010), was applied to either inbound or outbound traffic, therefore estimating that only the equivalent of 3% of Delhi's in-boundary VKT crosses the city boundary. Thus we hypothesize that in mega-cites, VKT's attributed to trans-boundary traffic may be negligible due to the high amounts of concurrent in-boundary traffic.

The other critical component of the vehicular benchmark is fuel efficiencies of vehicles in Delhi. Because data on fuel efficiencies is not currently collected by any Indian government agency (Roychowdhury, Chattopadhyaya, Sen, & Chandola, 2008), estimates of tailpipe emissions from the Automotive Research Association of India (ARAI, 2007) were used as the basis by (Arora, Vyas, & Johnson, 2011) in estimating fuel efficiencies of Indian vehicles (see Table 5-5). We then coupled fuel efficiencies by vehicle type with Delhi's VKT to estimate fuel used in road transport. Upon allocating fuel use of outbound vehicle trips out, we estimate 2009 fuel use in Delhi road transport equal to; Gasoline = 1,547 million liters, Diesel = 1,128 million liters, and CNG = 692 million cubic meters.

Estimates of fuel used in road transportation shown above were computed from a number of widely-cited and trusted organizations. As fuel efficiencies are essential in our computations, values by (Arora, et al., 2011) used here were verified, and are in line with estimates published by (Bose & Sperling, 2001). The aggregate fuel use values above were compared to those published by the MPNG, which are strictly survey based, as fuel efficiencies are not tracked in India. The ministry reports uses of Gasoline = 1,027 million liters, and Diesel = 1,214 million liters, in Delhi for 2009. A number of possible sources could trigger the differences. Under-reporting by vendors is the first tangible possibility. Another is that MPNG does not disaggregate by fuel end-use, where about 25% of India's diesel is used in non-transportation services such as industry, power generation, and others (Singh et al., 2008).

The VKT approach adopted here is believed to be of higher quality because it uses data from reliable sources. Moreover, the estimates use transportation and energy/health models strictly used for motorized road transport.

Table 5-5: Surface transport fuel use in Delhi. By fuel type and vehicle type.

Fuel Type	Vehicle Type	Daily VKT (million) [a]	Fuel Efficiency * (km/L) [b]	Fuel Use (million liters)	Total Fuel Use, by Fuel Type
Petrol	Car-Small	31.1	13.3	825	1,547 million liters
	Car-Big	13.5	13.3	358	
	Two Wheelers	54.7	53.1	364	
Diesel	Car-Small	8.8	13.5	231	1,128 million liters
	Car-Big	11.6	11.9	346	
	Bus	0.5	3.6	55	
	Light Commercial Vehicles (LCV)	3.3	5.2	231	
	Heavy Commercial Vehicles (HCV)	2.4	2.8	266	
CNG	Car-Small	2.1	15.4 [c]	48.1 [d]	692 million cubic meters
	Car-Big	0.8	15.4 [c]	17.8 [d]	
	Bus	2.2	2.0 [c]	393.3 [d]	
	Auto (Rickshaws)	19.6	30.5 [c]	232.3 [d]	

a. Daily VKT in Delhi retrieved from CRRI (2009).
b. Average Fuel Efficiencies within Indian fleet, from Arora (2011) and ARAI (2007).
c. CNG fuel efficiencies shown in liters per cubic meter.
d. CNG fuel use shown in cubic meters.
*. Fuel efficiency is referred to as fuel economy in the US and reported in equivalent units, miles per gallon.

5.4.4.2 Air Travel Benchmarks

Jet fuel loaded and passenger traffic at Delhi's IGI airport was obtained directly from the airport. Jet fuel loaded in 2010 is reported as domestic travel = 551 million liters, and international travel = 1,214 million liters, and enplaned passengers are reported as 8.7, and 4.0, million passengers, for domestic and international travel, respectively (DIAL, 2011). A passenger survey was conducted at IGI to allocate jet fuel loaded to Delhi based on the proportion of outbound passengers at IGI who were associated with activities in Delhi, either as residents, business travelers, tourists leaving, or visitors of Delhi.

Survey results show that 25% of domestic passengers, and 47% of international passengers were traveling through Delhi from another town (see Table 5-5). Thus, 76% of domestic passengers, and 53% of international passengers can be deduced to have Delhi-related travel, which was used to allocate jet fuel loaded to Delhi. Allocating jet fuel and passengers to Delhi yields 414 million liters, and 644 million liters for domestic and international travel, respectively. Thus resulting in 56 liters/enplaned passenger, and 275 liters/enplaned passenger for domestic and international travel, respectively. Of the total jet fuel loaded at IGI, only the domestic portion was incorporated into Delhi's TBIF as required by international protocols (DIAL, 2011; UNFCCC, 2006).

5.4.4.3 Rail Travel Benchmarks

We used India's national GHG emissions inventory to determine that emissions from railways constitute 0.4% of the country's GHG emissions (MEF, 2010), mostly diesel combustion. A lack of data and the relatively lower importance in terms of total national GHG emissions guided us to ignore GHG emissions from rail in Delhi at this stage. With new local commuter rail being installed in Delhi, future work may incorporate GHG from rail by combining energy use of Indian railways (IRFCA, 2006), rail passenger kilometers traveled (PKT), and goods transported by rail (TWB, 2010).

Table 5-6: Results from airport survey conducted at the Delhi International Airport. 111 travelers: 52 domestic travelers, 59 international travelers.

Question	Answer Choice	% Responses	
		Domestic Terminal (n = 52)	International Terminal (n = 59)
1. Are you a resident of Delhi?	a. Yes	27%	27%
	b. No	73%	73%
2. If not a resident of Delhi, are you leaving after a…	a. Business or work related trip in Delhi	35%	5%
	b. Holiday or other special occasion in Delhi	6%	0%
	c. Visited friends or relatives in Delhi	6%	15%
	d. Sightseeing tour/vacation in Delhi	2%	5%
	e. None of the above: I am just passing through Delhi from another city or town	25%	47%
3. Where did you initiate your trip?	a. My own home	31%	47%
	b. Hotel in Delhi	6%	12%
	c. Relatives or friends home in Delhi	10%	15%
	d. Workplace in Delhi	21%	0%
	e. Drove into Delhi from outside of Delhi	8%	24%
	f. Flew into Delhi from another city/country, and simply flying through Delhi	25%	2%
	g. Other	0%	0%
4. Will you be willing to share the purpose of your trip?	a. Business of work related trip	65%	47%
	b. Holiday or other special occasion	13%	19%
	c. Visiting friends or relatives	13%	15%
	d. Vacation	6%	12%
	e. Personal	2%	5%
	f. Other	0%	2%
5. Which mode of transport did you use to come to the airport today?	a. Metro	9%	7%
	b. Government Bus	5%	3%
	c. Taxi	68%	62%
	d. My own car	18%	28%

5.4.4.4 Emissions Factors

The combustion EFs of fuels used in transportation within Delhi are consistent with IPCC 2006, and equal to those used in India's national GHG inventory (MEF, 2010). The EFs from fuel combustion are: Gasoline = 2.4 kg-CO_2e/liter, Diesel = 2.9 kg-CO_2e/liter, and Jet Fuel = 2.7 kg-CO_2e/liter. EF associated with diesel production has been retrieved from (Whitaker, 2007), who estimated an EF from diesel production in India equal to 0.5 kg-CO_2e/liter. Because the distillation temperature of diesel occurs within a similar range to that of jet fuel kerosene, 200-300 °C, it was assumed that both diesel and jet fuel have similar production EF, as has been previously assumed (Hillman & Ramaswami, 2010;

Kennedy, et al., 2009). Production EF for gasoline and CNG in India were not attainable, so the following assumptions were made. For gasoline, because distillation occurs at lower temperatures than that of diesel, the worst case EF was assumed to be equal to diesel (0.5 kg-CO_2e/liter); and CNG was assumed to equal the median value of those reported in (Kennedy, et al., 2009), equal to 0.3 kg-CO_2e/cubic-meter.

5.4.5 Embodied Energy of Materials Use

Embodied energy incorporated in TBIF includes that for: wastewater (WW) treatment (T)/pumping (P), water treatment (T)/pumping (P), food production, and cement production since these activities are not already counted in in-boundary GHG described in previous sections. Although WW and water treatment occurs within Delhi, subtracting these energy uses from the above estimates allows us to clearly illustrate embodied energy used in WW and water operations.

5.4.5.1 Embodied Energy of Materials Benchmarks

Wastewater (WW) treatment in Delhi is tracked and reported by the Delhi Jal Board, which treated 1,584 million liters/day of WW in 2009 (MUD, 2010), using a total annual of 40 million kWh (T = 17, P = 23, million kWh) (DJB, 2011). Municipal treated water supply totaled 3,125 million liters/day (MUD, 2010), using a total annual of 266 million kWh (T = 242, P = 24, million kWh) (DJB, 2011).

For estimating average food consumption by Indian households, (Miller & Ramaswami, 2011) used statistics from the Food and Agriculture Organization (FAO), thus resulting in 3,616 kg-food/HH (or 0.78 tonnes-food/resident), thereby estimating the 2009 food supply to Delhi as 13.8 million tonnes. This likely under estimates all food used in Delhi, as it excludes food in commercial/tourist establishments which may be a large proportion of the city’s economy. Further, there are an estimated 45,285 non-milk heads-cattle, 45,760 milk heads-cattle, and 304,655 heads-buffaloes within Delhi boundaries (DAH, 2010), which we use in the next sub-section for estimating direct methane emissions from enteric fermentation within Delhi boundaries. These in-boundary estimates associated with milk-producing cattle are subtracted from the trans-boundary GHG emissions from food production.

As previously discussed, there is no cement production within Delhi boundaries (CMA, 2010), thus confirming that Delhi cement flows can be treated as trans-boundary. Community-wide cement use in Delhi was obtained from the Cement Manufacturers Association (CMA), and is estimated at 0.24 tonnes/capita/yr (CMA, 2010).

5.4.5.2 Emissions Factors

Water and wastewater is supplied from within Delhi, and thus relevant energy use has been subtracted from Delhi's in-boundary energy use total, avoiding double count. End-use energy intensity used in 2009 for treating and pumping WW and water are obtained from (DJB, 2011) and (MUD, 2010). The resulting ratios of energy-to-water are, 0.03 Wh/liter of treated WW, 0.04 Wh/liter of pumped WW, 0.21 Wh/liter of treated water, and 0.02 Wh/liter of pumped water.

The Food EF has been retrieved from (Miller & Ramaswami, 2011), who estimated a per unit weight EF from Indian food production (agriculture only). Their food EF quantifies direct methane and nitrous oxide emissions from Indian agriculture, eliminating double counting of energy used in processing or transporting food. The food EF, including emissions from cattle is 0.45 mt-CO_2e/mt-food.

This study also considered direct methane emissions from enteric fermentation in Delhi. GHG emissions per cattle in Delhi were retrieved from (Sharma, et al., 2002b) who estimated EF from non-milk producing cattle as 525 kg-CO_2e/head/yr, for milk producing cattle as 966 kg-CO_2e/head/yr, and buffaloes as 1,155 kg-CO_2e/head/yr, yielding GHG emissions from cattle within Delhi boundaries to be 419,855 mt-CO_2e. Lastly, to avoid double counting, we subtract cattle GHG emissions from the above food EF, resulting in a new food EF (less in-boundary cattle), equal to 0.42 mt-CO_2e/mt-food.

Cement EF is well documented, and obtained from the literature. In this study, we applied an Indian EF from cement production equal to 0.93 mt-CO_2e/mt-cement (Hendriks, Worrell, Jager, Blok, & Riemer, 2004).

5.5 Conclusions

This chapter presented the methodology and results from applying the Trans-Boundary Infrastructure Footprint (TBIF) GHG emissions accounting approach in the rapidly developing city of Delhi, India. The objectives were to 1) describe data availability for implementing the TBIF in Delhi, 2) identify methodological differences between India and US-based implementation of the TBIF, and 3) compare broad energy use metrics between Delhi and US cities, demonstrated by Denver which has previously been shown to be similar to US averages.

Multiplying Delhi's 2009 material/energy flows (MFA) with associated emissions factors (EF) resulted in total TBIF GHG emissions equal to 40.3 million mt-CO_2e. Normalizing by population, Delhi's TBIF GHG emissions are 2.3 mt-CO_2e/capita; as expected, they are higher than the 1.5 mt-CO_2e/capita reported nationally (MEF, 2010), since Delhi represents 1.5% of India's population. Of Delhi's 2009 TBIF GHG emissions, in-boundary activities represented 68% (or 27.3 million mt-CO_2e) and trans-boundary 32% (or 13 million mt-CO_2e). The buildings sector (including residential, commercial, industrial) represented 42% of Delhi's GHG emissions. GHGs from road transportation represented 21%, waste 2.7%, water/WW pumping and treatment 0.5%, and cattle 1%. See Figure 5-1.

The TBIF method was found to be very useful for measuring a comprehensive GHG footprint for Delhi. Most of the required data for applying the TBIF for Delhi was found to be available, and it's possible that this could have been a result of higher levels of government reporting, as Delhi is a city-state. There were some methodological differences that were a result of data constraints, though the method was mostly replicated. In fact, the method applied for Delhi helped to identify clear data needs and knowledge gaps where supplementary primary data collection is needed. For example, in the US, the method has used regional transportation models for allocating jet fuel use to multiple cities served by a single regional airport. In Delhi, the absence of a transportation model required the use of airport surveys to allocate total jet fuel used at the Delhi International Airport, to Delhi. In many ways, implementing TBIF was easier in a large mega city such as Delhi. Trans-boundary VKT was found to be a small contribution (3%) of in-boundary VKT, thus origin-destination allocation of travel between cities in a commuter-shed is not needed. Further, CMA reports annual cement use in city-states such as Delhi, while obtaining this data has been challenging in US cities, and likely will also be the case in other Indian cities that are not city-states.

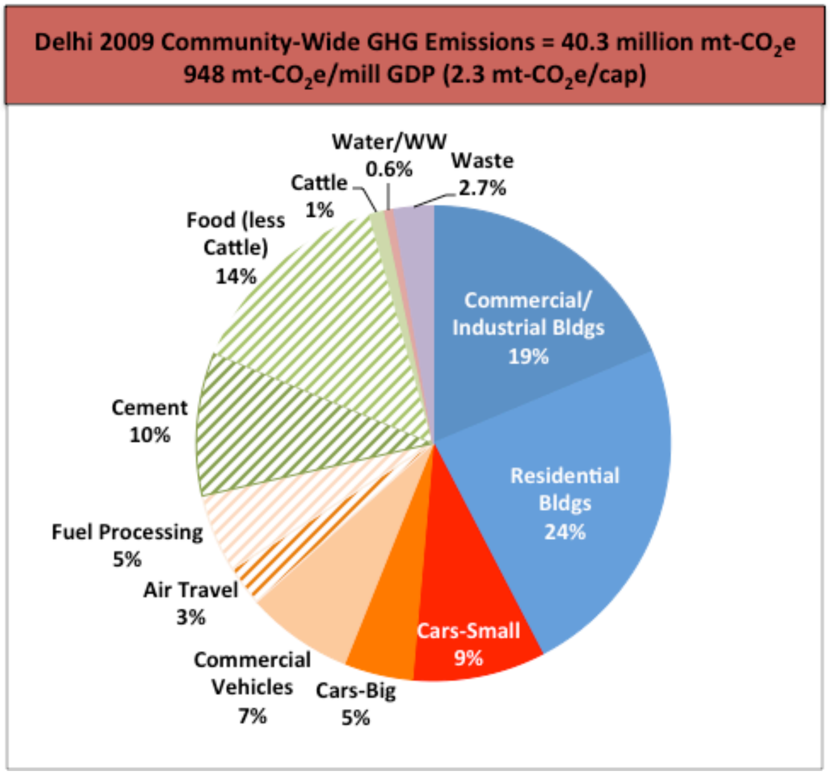
Comparing broad metrics across two distinct cities, Delhi, India and Denver, CO, USA, present compelling results. Delhi's per capita GHG emissions are higher than India's (2.4 vs. 1.5; mt-CO_2e/cap), reflecting low urbanization levels in India. Both Ramaswami et al. (2008) and Hillman & Ramaswami (2010) note that Denver's GHG emissions are fairly close to the US national average, at about 25 mt-CO_2e/cap, due to 80% U.S. urbanization, i.e., 80% of the population lives in urban areas. Delhi's per capita GHG are almost a factor of ten lower than Denver's, explained by a multitude of factors. For example, Delhi's residential primary energy use of 3,693 MJ/HH/mo is a factor of three lower than Denver (10,551 MJ/HH/mo); and road transportation travel in Delhi (8.8 VKT/cap/day) is about four times below Denver (39 VKT/cap/day). Most notable are the differences in commercial-industrial energy end-use which are significantly lower in Delhi (2,064 MJ/capita/yr) compared to Denver (76,166 MJ/capita/yr). Similarly, commercial floor area per capita is much less in Delhi than Denver (1.46 sq-meter/capita vs. 36.7 sq-meter/capita). Even though the data suggests much less commercial activity in Delhi versus Denver, the economic GHG intensity provides additional insights.

Delhi's economic GHG intensity is twice as large as Denver's, 948 mt-CO_2e/GDP versus 413 mt-CO_2e/GDP, respectively. Such difference may be attributed to economic structure, where Denver is predominantly a tertiary sector producer, and Delhi a secondary and tertiary sector producer. Other notable differences are shown in Table 5-7. Delhi's GDP/capita is about ten times lower than Denver's (6,037 USD/capita vs. 57,560

USD/capita). In terms of population density, Delhi is significantly denser than Denver (9,340 cap/sq-km vs. 1,463 cap/sq-km). Homes in Delhi are smaller than homes in Denver (46.8 sq-meter/HH vs. 102.8 sq-meter/HH).

As shown, the TBIF method can have important environmental and policy implications for Delhi and other rapidly industrializing cities. The TBIF shows an additional 32% of Delhi's GHG emissions attributed to trans-boundary activities, thereby suggesting innovative cross-sector strategies towards urban sustainability, particularly in electricity generation, and building materials/cement sectors. Comparing Delhi to Denver, supply-chain GHG from cement use in construction contributed 10% to Delhi's TBIF, versus only 2% in Denver (Ramaswami et al. 2008); in contrast, waste/wastewater GHG were a lower proportion in Denver (at 1%) versus Delhi (at 3.3%) – these data suggest that other construction materials not studied here may also be a significant part of Delhi's TBIF. The TBIF for Delhi shows that both waste-management and material exchange symbiosis can be important in reducing the TBIF of cities in rapidly industrializing countries.

Figure 5-1: TBIF for Delhi, India, 2009 expanded GHG footprint.



*** In-Boundary GHGs are represented by solid, and Trans-Boundary GHGs are represented in hatched.**

Table 5-7: Comparison of broad Energy & Material Use, and Demographic metrics for Delhi, India and Denver, CO, USA.

Activity Sector	Metric	Delhi, India *(948 mt-CO_2e/GDP)* *(2.3 mt-CO_2e/cap)*	Denver, CO, USA [j] *(413 mt-CO_2e/GDP)* *(25 mt-CO_2e/cap)*
Buildings Energy Use & industrial process	**Residential Intensity:**		
	kWh/HH/mo	191 [a]	545
	cubic meters/HH/mo	n/a	124
	liters-LPG/HH/mo	25.3 [b]	n/a
	Liters-Kerosene/HH/mo	3.4 [b]	n/a
	Total MJ/HH/mo (end-use)	1,489 [#]	6,728
	Total Primary (MJ/HH/mo)	3,693 [#]	10,551 [#]
	Commercial-Industrial Intensity:		
	kWh/GDP/yr	0.21 [#]	0.15 [#]
	Other stationary fuels MJ/GDP/yr	0.13 [#]	0.78 [#]
	Total MJ/GDP/yr (end-use)	0.87 [#]	1.32 [#]
	Total MJ/capita/yr (end-use)	2,064 [#]	76,166 [#]
	Total Primary (MJ/GDP/yr)	3.5 [#]	2.4 [#]
	Industrial Process: tonnes of waste/capita/yr	0.16 [c]	1.1
	Electricity EF: *kg-CO_2e/kWh*	*0.82 {0.83}*	*0.75 {0.64}*
Transportation Energy Use	**Surface Travel Intensity:** VKT/capita/day	8.8 [d]	38.6
	Air Travel: liters-jet fuel/enplaned passenger (domestic)	56 [e]	72
Materials Use, and Demographics	**Water:** treated water/WW (1000 liters/capita/yr)	95 [f]	560
	Cement: mt-cement/capita/yr	0.24 [g]	0.50
	GDP/capita *($/capita)*	$6,037 [h]	$57,560 [k]
	Total local population *(capita)*	17,601,000 [i]	579,744
	Population Density *(capita/sq-km)*	9,340 [i]	1,463
	Total homes *(HH)*	3,815,104 [i]	256,524
	Residential floor area (sm_r/HH)	46.8 *	102.8
	Total commercial floor area (million sm_c)	25.7 *	21.3
	Total floor area per capita (sm/cap)	10.1 [#]	74.5
	Total city area *(sq-km)*	1,886 [#]	396

a. (DERC, 2009); **b.** (MPNG, 2009); **c.** (DPCC, 2010); **d.** (CRRI, 2009); **e.** (DIAL, 2010); **f.** (MUD, 2010); **g.** (CMA, 2010); **h.** (DES, 2009); **i.** (DCO, 2009); **j.** (Hillman & Ramaswami, 2010); **k.** (BEA, 2009); **#.** Calculated; ***.** Estimated, and may not represent most accurate statistic.
Electricity EF: No brackets represent local EF. {brackets} represent national EF.

6. Conclusion, Contributions, Future Work & Protocols

6.1 Conclusions

This thesis explored mathematical relationships, approximations, implementation challenges, and policy relevance for three city-scale GHG emission accounting methods. The three methods, Purely Territorial, Trans-Boundary Infrastructure Supply-Chain Footprint (TBIF), and Consumption-Based Footprint (CBF), each have a unique representation of a city.

Mathematical relationships showed that neither TBIF nor CBF provided a more holistic accounting of trans-boundary GHGs, and in fact showed that the two methods are linked. These relationships were also used to define a typology of cities defined as *net-producers*, *trade-balanced*, and *net-consumers* in terms of their GHGs embodied in trade. The typology classification elucidated important differences in the total GHG footprint (territorial plus import supply-chains) for cities.

Through a meta-analysis of 21 US cities, Territorial GHGs were shown to be as small as 37% of the total footprint for a net-consumer city, and as large as 68% for a net-producer city. The TBIF was shown to capture 75% (n=2) of the total footprint for net-producer, 63% (n=11) for trade-balanced, and 62% (n=8) for net-consumer cities. Meanwhile, CBF captures 35% (n=2), 57% (n=11), and 71% (n=8) of the total footprint for net-producer, trade-balanced, and net-consumer cities, respectively. In total TBIF captures more than 60% of the total footprint for all three-city types, and CBF coverage is largely dependent on city type.

The meta-analysis showed that a number of trans-boundary infrastructure sectors had high correlation ($R^2>0.70$) between community GDP and GHG in community-wide (residential-commercial-industrial) use of the same sectors. These sectors (electricity generation, air travel, fuel refining, along with the production of food, cement, and iron &

steel) might be well suited for allocation to cities based on their use in citywide residential-commercial-industrial activities in the TBIF method.

Various suitable metrics were explored to appropriately compare cities using GHGs computed by the three methods. For territorial GHG, neither $GHG^{Territorial}$/capita nor $GHG^{Territorial}$/GDP reflected urban efficiency of cities. For the three versions of TBIF evaluated, GHG^{TBIF}/GDP yielded stronger correlations with an urban efficiency index (UEI) as follows: with only electricity allocated (R^2=0.62); Scopes 1+2+3 w/o allocating (R^2=0.75); and Scopes 1+2+3 w/ allocating (R^2=0.77). Here again GHG^{TBIF}/cap showed poor correlation (R^2=0.1) with the UEI as expected from production-based accounting. In contrast, GHG^{CBF}/cap showed an improved correlation (R^2=0.4) with the UEI, and GHG^{CBF}/cap correlated well (R^2=0.76) with per capita expenditures. These data suggest that GHG^{TBIF}/GDP is the appropriate metric for comparing cities based on their urban efficiency, and that GHG^{CBF}/cap is appropriate for viewing cities from a consumption perspective. For 21 US cities, GHG^{TBIF}/GDP ranged from 154 mt-CO_2e/GDP to 747 mt-CO_2e/GDP, and GHG^{CBF}/capita ranged from 15 mt-CO_2e/cap to 32 mt-CO_2e/capita.

This thesis also presented results from the TBIF implemented in Delhi, India. The objectives of this part of the research were to explore issues of data availability and transferability of methods from the US to rapidly industrializing nations. We found that most methods translated well from the US to India, and that data required for completing the TBIF was reasonably available. In all, fieldwork showed sufficient availability and adaptability of TBIF methodology from the US to India yielding GHG^{TBIF} equal to 948 mt-CO_2e/GDP in Delhi vs. 413 mt-CO_2e/GDP in Denver. Broad energy use metrics between Delhi and Denver are shown to help describe differences between the two cities.

6.2 Contributions

This thesis makes a number of unique contributions to the study and understanding of GHG emissions associated with cities. The contributions of this thesis are:

- Presented the first side-by-side comparison of the three methods accounting for GHG emissions associated with cities
- Derived mathematical relationships between the three methods for cities
- Clearly articulated a need for studying cities by typology
- Clearly articulated the Total Upstream Footprint of cities and its coverage by the three methods
- Provided a better understanding of metrics for comparing cities on the basis of efficiencies
- Conducted international field research in Delhi, India, leading to the first TBIF for Delhi.

6.3 Future Work & Protocols

This thesis answered a number of key questions that are important in the understanding the GHGs associated with cities, and number of areas presented in this thesis can be pursued in future work towards the development of GHG emission accounting protocols. However, cities throughout the world still require additional resources to make progress in the direction of their respective climate goals. In the US and abroad, continued collaboration is required to develop reasonable protocols tailored to different city types, that allow cities to maximize opportunities for GHG mitigation. For example, net-producer cities, which are shown to have large territorial GHG relative to GHG embodied in imports, can have greater GHG mitigation impacts by focusing their efforts on greening their local businesses and industries. Although net-consumer cities have mitigation opportunities through their local businesses and industries, consumer awareness campaigns aimed at lowering consumption (energy and other goods/services consumed by households) may be better suited for these city types. Large cities can benefit from a production-based protocol as CBF may be approximated through TBIF, and data for conducting TBIF have been shown to be readily available in many cities.

In this thesis we also uncovered some of the data challenges involved with using downscaled input-output models for energy and environmental modeling. In their current form, downscaled IO models are designed to be used for economic impact analysis, and are not designed to be used with high accuracy for energy and environmental analysis. Additional collaborations between IO developers and researchers, which can help flag and correct these mismatches between dollar- and energy-flows, can have multiple outcomes for GHG emission accounting and future work. Two potential outcomes are:

1. If IO tables can accurately capture trans-boundary vs. in-boundary contributions, this could become an important feature of such data sets.
2. Improved IO models at the city scale may capture the entire footprint associated with cities.

In the meantime however, some of the other analysis presented in this thesis can have important implications in protocol development.

The TBIF captures the majority of the total GHG footprint, ranging from 62% – 75% for 21 US cities. TBIF was shown to correlate with the urban efficiency performance of cities on a consistent basis. Implementation and data for TBIF has shown to be readily available for US and Indian cities. TBIF provides a holistic account of GHGs, and TBIF is approximately equal to CBF (TBIF≈CBF) for trade-balanced cities, of which large cites may be. Lastly, as TBIF intrinsically follows the five principles of GHG accounting defined by the WRI (Relevance, Completeness, Consistency, Transparency, Accuracy), TBIF is well suited for international GHG protocols that seek to compare cities.

Appendix A: Energy Use Data Retrieved From GHG Inventories, and IMPLAN

A1. Building Energy Use

ELECTRICITY

		Electricity Use		% community-wide electricity use that is generated locally	
		Unadjusted IMPLAN	Community GHG Inventory *[state benchmark]*	Unadjusted IMPLAN	EPA eGRID *(local generation)*
Sacramento, CA	Residential Intensity	721 kWh/HH/mo	748 *[580]* kWh/HH/mo	78%	61%
	Total Commercial-Industrial Use	7,245 GWh	5,774 GWh		
Napa, CA	Residential Intensity	830 kWh/HH/mo	623 *[580]* kWh/HH/mo	30%	1%
	Total Commercial-Industrial Use	689 GWh	563 GWh		
Boulder, CO	Residential Intensity	1,138 kWh/HH/mo	852 *[743]* kWh/HH/mo	60%	48%
	Total Commercial-Industrial Use	2,938 GWh	2,142 GWh		
Broomfield, CO	Residential Intensity	1,078 kWh/HH/mo	825 *[768]* kWh/HH/mo	0%	0%
	Total Commercial-Industrial Use	629 GWh	447 GWh		
Denver, CO	Residential Intensity	1,284 kWh/HH/mo	546 *[768]* kWh/HH/mo	91%	19%
	Total Commercial-Industrial Use	11,313 GWh	5,038 GWh		
Routt, CO	Residential Intensity	980 kWh/HH/mo	833 *[743]* kWh/HH/mo	98%	100%
	Total Commercial-Industrial Use	287 GWh	251 GWh		
Collier, FL	Residential Intensity	1,074 kWh/HH/mo	1,780 *[1,354]* kWh/HH/mo	24%	0%
	Total Commercial-Industrial Use	2,068 GWh	2,059 GWh		
Sarasota, FL	Residential Intensity	952 kWh/HH/mo	1,403 *[1,367]* kWh/HH/mo	43%	0%
	Total Commercial-Industrial Use	1,730 GWh	1,861 GWh		
Broward, FL	Residential Intensity	922 kWh/HH/mo	1,352 *[1,354]* kWh/HH/mo	18%	40%
	Total Commercial-Industrial Use	10,475 GWh	10,713 GWh		
Miami-Dade, FL	Residential Intensity	906 kWh/HH/mo	1,267 *[1,367]* kWh/HH/mo	65%	90%
	Total Commercial-Industrial Use	15,477 GWh	14,300 GWh		
Washoe,	Residential	966	700 *[1,022]*	43%	10%

NV	Intensity	kWh/HH/mo	kWh/HH/mo		
	Total Commercial-Industrial Use	3,566 GWh	2,863 GWh		
Tompkins, NY	Residential Intensity	547 kWh/HH/mo	564 *[554]* kWh/HH/mo	95%	100%
	Total Commercial-Industrial Use	786 GWh	486 GWh		
Westchester, NY	Residential Intensity	885 kWh/HH/mo	589 *[575]* kWh/HH/mo	90%	100%
	Total Commercial-Industrial Use	4,252 GWh	3,283 GWh		
Multnomah, OR	Residential Intensity	1,290 kWh/HH/mo	793 *[1,092]* kWh/HH/mo	90%	53%
	Total Commercial-Industrial Use	12,936 GWh	5,746 GWh		
Philadelphia, PA	Residential Intensity	1,097 kWh/HH/mo	507 *[851]* kWh/HH/mo	87%	5%
	Total Commercial-Industrial Use	7,973 GWh	8,969 GWh		
Roanoke, VA	Residential Intensity	1,090 kWh/HH/mo	1,261 *[1,247]* kWh/HH/mo	99%	0%
	Total Commercial-Industrial Use	758 GWh	517 GWh		
Loudoun, VA	Residential Intensity	1,183 kWh/HH/mo	1,472 *[1,247]* kWh/HH/mo	24%	0%
	Total Commercial-Industrial Use	2,627 GWh	2,153 GWh		
Snohomish, WA	Residential Intensity	1,402 kWh/HH/mo	994 *[1,114]* kWh/HH/mo	92%	10%
	Total Commercial-Industrial Use	4,319 GWh	3,184 GWh		
METRO, OR	Residential Intensity	1,208 kWh/HH/mo	714 *[1,071]* kWh/HH/mo	84%	31%
	Total Commercial-Industrial Use	21,071 GWh	12,101 GWh		
New York City	Residential Intensity	800 kWh/HH/mo	374 *[554]* kWh/HH/mo	98%	46%
	Total Commercial-Industrial Use	48,316 GWh	34,088 GWh		
DVRPC, PA-NJ	Residential Intensity	1,032 kWh/HH/mo	842 *[851]* kWh/HH/mo	86%	63%
	Total Commercial-Industrial Use	47,360 GWh	36,776 GWh		

NATURAL GAS USE

		Natural Gas Use	
		Unadjusted IMPLAN	Community GHG Inventory *[state benchmark]*
Sacramento, CA	Residential Intensity	39 therms/HH/mo	33 *[34]* therms/HH/mo
	Total Commercial-Industrial Use	253 million therms	123 million therms
Napa, CA	Residential Intensity	46 therms/HH/mo	36 *[34]* therms/HH/mo
	Total Commercial-Industrial Use	26 million therms	13 million therms
Boulder, CO	Residential Intensity	45 therms/HH/mo	56 *[58]* therms/HH/mo
	Total Commercial-Industrial Use	58 million therms	72 million therms
Broomfield, CO	Residential Intensity	41 therms/HH/mo	60 *[59]* therms/HH/mo
	Total Commercial-Industrial Use	19 million therms	9 million therms
Denver, CO	Residential Intensity	49 therms/HH/mo	47 *[59]* therms/HH/mo
	Total Commercial-Industrial Use	335 million therms	246 million therms
Routt, CO	Residential Intensity	38 therms/HH/mo	52 *[58]* therms/HH/mo
	Total Commercial-Industrial Use	4 million therms	5 million therms
Collier, FL	Residential Intensity	23 therms/HH/mo	0.6 *[2]* therms/HH/mo
	Total Commercial-Industrial Use	35 million therms	7 million therms
Sarasota, FL	Residential Intensity	22 therms/HH/mo	2 *[2]* therms/HH/mo
	Total Commercial-Industrial Use	36 million therms	14 million therms
Broward, FL	Residential Intensity	19 therms/HH/mo	0.5 *[2]* therms/HH/mo
	Total Commercial-Industrial Use	235 million therms	38 million therms
Miami-Dade, FL	Residential Intensity	19 therms/HH/mo	9 *[2]* therms/HH/mo
	Total Commercial-Industrial Use	385 million therms	34 million therms
Washoe, NV	Residential Intensity	21 therms/HH/mo	50 *[34]* therms/HH/mo
	Total Commercial-Industrial Use	84 million therms	71 million therms
Tompkins, NY	Residential Intensity	14 therms/HH/mo	33 *[46]* therms/HH/mo
	Total Commercial-Industrial Use	52 million therms	26 million therms
Westchester, NY	Residential Intensity	45 therms/HH/mo	51 *[48]* therms/HH/mo
	Total Commercial-Industrial Use	146 million therms	143 million therms

Multnomah, OR	Residential Intensity	19 therms/HH/mo	30 *[25]* therms/HH/mo
	Total Commercial-Industrial Use	300 million therms	164 million therms
Philadelphia, PA	Residential Intensity	30 therms/HH/mo	53 *[35]* therms/HH/mo
	Total Commercial-Industrial Use	160 million therms	279 million therms
Roanoke, VA	Residential Intensity	23 therms/HH/mo	54 *[23]* therms/HH/mo
	Total Commercial-Industrial Use	15 million therms	18 million therms
Loudoun, VA	Residential Intensity	26 therms/HH/mo	46 *[23]* therms/HH/mo
	Total Commercial-Industrial Use	60 million therms	23 million therms
Snohomish, WA	Residential Intensity	33 therms/HH/mo	27 *[26]* therms/HH/mo
	Total Commercial-Industrial Use	74 million therms	80 million therms
METRO, OR	Residential Intensity	25 therms/HH/mo	25 *[24]* therms/HH/mo
	Total Commercial-Industrial Use	422 million therms	342 million therms
New York City	Residential Intensity	21 therms/HH/mo	37 *[46]* therms/HH/mo
	Total Commercial-Industrial Use	1,495 million therms	1,138 million therms
DVRPC, PA-NJ	Residential Intensity	29 therms/HH/mo	48 *[50]* therms/HH/mo
	Total Commercial-Industrial Use	1,419 million therms	1,407 million therms

Appendix B: Sector Trade For Three Communities

Routt, Colorado

Sector Description	Export Value (million $)
Real Estate	$202
Coal Mining	$164
Other amusement- gambling- and recreation industries	$99
Power generation and supply	$61
Food services and drinking places	$51
Hotels and motels- including casino hotels	$42
Cattle ranching and farming	$28
Commercial and institutional buildings	$24
Hospitals	$19
Gasoline Stations	$18

Denver, Colorado

Sector Description	Export Value (million $)
Oil & Natural Gas Extraction	$5,994
Real Estate	$5,437
Air transportation	$2,940
Wholesale services	$2,751
Telecommunications	$2,501
Securities, commodity contracts, investments, and related services	$2,266
Management of companies	$1,483
Legal services	$1,416
Advertising services	$967
Software	$820

Sarasota, Florida

Sector Description	Export Value (million $)
Professional and technical services	$600
Metal window and door manufacturing	$505
Real estate	$461
Telecommunications	$289
Insurance agencies	$212
Offices of physicians-dentists-other health	$185
Services to buildings and dwellings	$181
Employment services	$179
Paint and coating manufacturing	$133
Securities, commodity contracts, investments, and related services	$111

Appendix C: IMPLAN Sector Scheme

IMPLAN Sector Code	NAICS Sector Code	Sector Description
3001	1111A0	Oilseeds
3002	1111B0	Grains
3003	111200	Vegetables and melons
3004	1113A0	Fruit
3005	111335	Tree nuts
3006	111400	Greenhouse, nursery, and floriculture products
3007	111910	Tobacco
3008	111920	Cotton
3009	1119A0	Sugarcane and sugar beets
3010	1119B0	All other crop farming products
3011	1121A0	Cattle from ranches and farms
3012	112120	Dairy cattle and milk products
3013	112300	Poultry and egg products
3014	112A00	Animal products, except cattle, poultry and eggs
3015	113A00	Forest, timber, and forest nursery products
3016	113300	Logs and roundwood
3017	114100	Fish
3018	114200	Wild game products, pelts, and furs
3019	115000	Agriculture and forestry support services
3020	211000	Oil and natural gas
3021	212100	Coal
3022	212210	Iron ore
3023	212230	Copper, nickel, lead, and zinc
3024	2122A0	Gold, silver, and other metal ore
3025	212310	Natural stone
3026	212320	Sand, gravel, clay, and ceramic and refractory minerals
3027	212390	Other nonmetallic minerals
3028	213111	Oil and gas wells
3029	213112	Support services for oil and gas operations
3030	21311A	Support services for other mining
3031	221100	Electricity, and distribution services
3032	221200	Natural gas, and distribution services
3033	221300	Water, sewage treatment, and other utility services
3034	230101	Newly constructed nonresidential commercial and health care structures
3035	230102	Newly constructed nonresidential manufacturing structures
3036	230103	Other newly constructed nonresidential structures

3037	230201	Newly constructed residential permanent site single- and multi-family structures
3038	230202	Other newly constructed residential structures
3039	230301	Maintained and repaired nonresidential structures
3040	230302	Maintained and repaired residential structures
3041	311111	Dog and cat food
3042	311119	Other animal food
3043	311210	Flour and malt
3044	311221	Corn sweetners, corn oils, and corn starches
3045	31122A	Soybean oil and cakes and other oilseed products
3046	311225	Shortening and margarine and other fats and oils products
3047	311230	Breakfast cereal products
3048	31131A	Raw and refined sugar from sugar cane
3049	311313	Refined sugar from sugar beets
3050	311320	Chocolate cacao products and chocolate confectioneries
3051	311330	Chocolate confectioneries from purchased chocolate
3052	311340	Nonchocolate confectioneries
3053	311410	Frozen foods
3054	311420	Canned, pickled and dried fruits and vegetables
3055	31151A	Fluid milk and butter
3056	311513	Cheese
3057	311514	Dry, condensed, and evaporated dairy products
3058	311520	Ice cream and frozen desserts
3059	31161A	Processed animal (except poultry) meat and rendered byproducts
3060	311615	Processed poultry meat products
3061	311700	Seafood products
3062	311810	Bread and bakery products
3063	311820	Cookies, crackers, and pasta
3064	311830	Tortillas
3065	311910	Snack foods including nuts, seeds and grains, and chips
3066	311920	Coffee and tea
3067	311930	Flavoring syrups and concentrates
3068	311940	Seasonings and dressings
3069	311990	All other manufactured food products
3070	312110	Soft drinks and manufactured ice
3071	312120	Beer, ale, malt liquor and nonalcoholic beer
3072	312130	Wine and brandies
3073	312140	Distilled liquors except brandies
3074	3122A0	Cigarettes, cigars, smoking and chewing tobacco, and reconstituted tobacco
3075	313100	Fiber filaments, yarn, and thread
3076	313210	Broadwoven fabrics and felts

3077	313220	Woven and embroidered fabrics
3078	313230	Nonwoven fabrics and felts
3079	313240	Knitted fabrics
3080	313310	Finished textiles and fabrics
3081	313320	Coated fabric coating
3082	314110	Carpets and rugs
3083	314120	Curtains and linens
3084	314910	Textile bags and canvas
3085	314990	All other textile products
3086	315100	Knit apparel
3087	315210	Cut and sewn apparel from contractors
3088	315220	Mens and boys cut and sewn apparel
3089	315230	Womens and girls cut and sewn apparel
3090	315290	Other cut and sew apparel
3091	315900	Apparel accessories and other apparel
3092	316100	Tanned and finished leather and hides
3093	316200	Footwear
3094	316900	Other leather and allied products
3095	321100	Dimension lumber and preserved wood products
3096	32121A	Veneer and plywood
3097	32121B	Engineered wood members and trusses
3098	321219	Reconstituted wood products
3099	321910	Wood windows and doors and millwork
3100	321920	Wood containers and pallets
3101	321991	Manufactured homes (mobile homes)
3102	321992	Prefabricated wood buildings
3103	321999	All other miscellaneous wood products
3104	322110	Wood pulp
3105	322120	Paper from pulp
3106	322130	Paperboard from pulp
3107	322210	Paperboard containers
3108	32222A	Coated and laminated paper, packaging paper and plastics film
3109	32222B	All other paper bag and coated and treated paper
3110	322230	Paper and paperboard stationary products
3111	322291	Sanitary paper products
3112	322299	All other converted paper products
3113	323110	Printed materials
3114	323120	Printing support services
3115	324110	Refined petroleum products
3116	324121	Asphalt paving mixtures and blocks
3117	324122	Asphalt shingles and coating materials

3118	324191	Petroleum lubricating oils and greases
3119	324199	All other petroleum and coal products
3120	325110	Petrochemicals
3121	325120	Industrial gas
3122	325130	Synthetic dyes and pigments
3123	325181	Alkalies and chlorine
3124	325182	Carbon black
3125	325188	All other basic inorganic chemicals
3126	325190	Other basic organic chemicals
3127	325211	Plastics materials and resins
3128	325212	Synthetic rubber
3129	325220	Artificial and synthetic fibers and filaments
3130	325310	Fertilizer
3131	325320	Pesticides and other agricultural chemicals
3132	325411	Medicines and botanicals
3133	325412	Pharmaceutical preparations
3134	325413	In-vitro diagnostic substances
3135	325414	Biological products (except diagnostic)
3136	325510	Paints and coatings
3137	325520	Adhesives
3138	325610	Soaps and cleaning compounds
3139	325620	Toilet preparations
3140	325910	Printing inks
3141	3259A0	All other chemical products and preparations
3142	326110	Plastics packaging materials and unlaminated films and sheets
3143	326121	Unlaminated plastics profile shapes
3144	326122	Plastics pipes and pipe fittings
3145	326130	Laminated plastics plates, sheets (except packaging), and shapes
3146	326140	Polystyrene foam products
3147	326150	Urethane and other foam products (except polystyrene)
3148	326160	Plastics bottles
3149	32619A	Other plastics products
3150	326210	Tires
3151	326220	Rubber and plastics hoses and belts
3152	326290	Other rubber products
3153	32711A	Pottery, ceramics, and plumbing fixtures
3154	32712A	Bricks, tiles, and other structural clay products
3155	32712B	Clay and nonclay refractory products
3156	327211	Flat glass
3157	327212	Other pressed and blown glass and glassware
3158	327213	Glass containers

3159	327215	Glass products made of purchased glass
3160	327310	Cement
3161	327320	Ready-mix concrete
3162	327330	Concrete pipes, bricks, and blocks
3163	327390	Other concrete products
3164	3274A0	Lime and gypsum products
3165	327910	Abrasive products
3166	327991	Cut stone and stone products
3167	327992	Ground or treated mineral and earth products
3168	327993	Mineral wool
3169	327999	Miscellaneous nonmetallic mineral products
3170	331110	Iron and steel and ferroalloy products
3171	331200	Steel products from purchased steel
3172	33131A	Aluminum products
3173	331314	Aluminum alloys
3174	33131B	Aluminum products from purchased aluminum
3175	331411	Copper
3176	331419	Nonferrous metals (except copper and aluminum)
3177	331420	Rolled, drawn, extruded and alloyed copper
3178	331490	Rolled, drawn, extruded and alloyed nonferrous metals (except copper and aluminum)
3179	331510	Ferrous metals
3180	331520	Nonferrous metals
3181	33211A	All other forged, stamped, and sintered metals
3182	332114	Custom roll formed metals
3183	33211B	Crowned and stamped metals
3184	33221A	Cutlery, utensils, pots, and pans
3185	33221B	Handtools
3186	332310	Plates and fabricated structural products
3187	332320	Ornamental and architectural metal products
3188	332410	Power boilers and heat exchangers
3189	332420	Metal tanks (heavy gauge)
3190	332430	Metal cans, boxes, and other metal containers (light gauge)
3191	33299A	Ammunition
3192	33299B	Arms, ordnance, and accessories
3193	332500	Hardware
3194	332600	Spring and wire products
3195	332710	Machined products
3196	332720	Turned products and screws, nuts, and bolts
3197	332800	Coated, engraved, heat treated products
3198	33291A	Valves and fittings other than plumbing
3199	332913	Plumbing fixture fittings and trims

3200	332991	Balls and roller bearings
3201	332996	Fabricated pipes and pipe fittings
3202	33299C	Other fabricated metals
3203	333111	Farm machinery and equipment
3204	333112	Lawn and garden equipment
3205	333120	Construction machinery
3206	333130	Mining and oil and gas field machinery
3207	33329A	Other industrial machinery
3208	333220	Plastics and rubber industry machinery
3209	333295	Semiconductor machinery
3210	33331A	Vending, commercial, industrial, and office machinery
3211	333314	Optical instruments and lens
3212	333315	Photographic and photocopying equipment
3213	333319	Other commercial and service industry machinery
3214	33341A	Air purification and ventilation equipment
3215	333414	Heating equipment (except warm air furnaces)
3216	333415	Air conditioning, refrigeration, and warm air heating equipment
3217	333511	Industrial molds
3218	33351A	Metal cutting and forming machine tools
3219	333514	Special tools, dies, jigs, and fixtures
3220	333515	Cutting tools and machine tool accessories
3221	33351B	Rolling mills and other metalworking machinery
3222	333611	Turbines and turbine generator set units
3223	333612	Speed changers, industrial high-speed drives, and gears
3224	333613	Mechanical power transmission equipment
3225	333618	Other engine equipment
3226	333911	Pumps and pumping equipment
3227	333912	Air and gas compressors
3228	333920	Material handling equipment
3229	333991	Power-driven handtools
3230	33399A	Other general purpose machinery
3231	333993	Packaging machinery
3232	333994	Industrial process furnaces and ovens
3233	33399B	Fluid power process machinery
3234	334111	Electronic computers
3235	334112	Computer storage devices
3236	33411A	Computer terminals and other computer peripheral equipment
3237	334210	Telephone apparatus
3238	334220	Broadcast and wireless communications equipment
3239	334290	Other communications equipment
3240	334300	Audio and video equipment

3241	334411	Electron tubes
3242	334412	Bare printed circuit boards
3243	334413	Semiconductor and related devices
3244	33441A	Electronic capacitors, resistors, coils, transformers, and other inductors
3245	334417	Electronic connectors
3246	334418	Printed circuit assemblies (electronic assemblies)
3247	334419	Other electronic components
3248	334510	Electromedical and electrotherapeutic apparatus
3249	334511	Search, detection, and navigation instruments
3250	334512	Automatic environmental controls
3251	334513	Industrial process variable instruments
3252	334514	Totalizing fluid meters and counting devices
3253	334515	Electricity and signal testing instruments
3254	334516	Analytical laboratory instruments
3255	334517	Irradiation apparatus
3256	33451A	Watches, clocks, and other measuring and controlling devices
3257	33461A	Software, blank audio and video media, mass reproduction
3258	334613	Magnetic and optical recording media
3259	335110	Electric lamp bulbs and parts
3260	335120	Lighting fixtures
3261	335210	Small electrical appliances
3262	335221	Household cooking appliances
3263	335222	Household refrigerators and home freezers
3264	335224	Household laundry equipment
3265	335228	Other major household appliances
3266	335311	Power, distribution, and specialty transformers
3267	335312	Motor and generators
3268	335313	Switchgear and switchboard apparatus
3269	335314	Relay and industrial controls
3270	335911	Storage batteries
3271	335912	Primary batteries
3272	335920	Communication and energy wires and cables
3273	335930	Wiring devices
3274	335991	Carbon and graphite products
3275	335999	All other miscellaneous electrical equipment and components
3276	336111	Automobiles
3277	336112	Light trucks and utility vehicles
3278	336120	Heavy duty trucks
3279	336211	Motor vehicle bodies
3280	336212	Truck trailers
3281	336213	Motor homes

3282	336214	Travel trailers and campers
3283	336300	Motor vehicle parts
3284	336411	Aircraft
3285	336412	Aircraft engines and engine parts
3286	336413	Other aircraft parts and auxiliary equipment
3287	336414	Guided missiles and space vehicles
3288	33641A	Propulsion units and parts for space vehicles and guided missiles
3289	336500	Railroad rolling stock
3290	336611	Ships
3291	336612	Boats
3292	336991	Motorcycles, bicycles, and parts
3293	336992	Military armored vehicles, tanks, and tank components
3294	336999	All other transportation equipment
3295	337110	Wood kitchen cabinets and countertops
3296	337121	Upholstered household furniture
3297	337122	Nonupholstered wood household furniture
3298	33712A	Metal and other household furniture (except wood)
3299	337127	Institutional furniture
3300	33721A	Wood television, radio, and sewing machine cabinets
3301	337212	Office furniture and custom architectural woodwork and millwork
3302	337215	Showcases, partitions, shelving, and lockers
3303	337910	Mattresses
3304	337920	Blinds and shades
3305	339112	Surgical and medical instrument, laboratory and medical instruments
3306	339113	Surgical appliances and supplies
3307	339114	Dental equipment and supplies
3308	339115	Ophthalmic goods
3309	339116	Dental laboratories
3310	339910	Jewelry and silverware
3311	339920	Sporting and athletic goods
3312	339930	Dolls, toys, and games
3313	339940	Office supplies (except paper)
3314	339950	Signs
3315	339991	Gaskets, packing and sealing devices
3316	339992	Musical instruments
3317	33999A	All other miscellaneous manufactured products
3318	339994	Brooms, brushes, and mops
3319	420000	Wholesale trade distribution services
3320	441000	Retail Services - Motor vehicle and parts OR BEA ALL RETAIL
3321	442000	Retail Services - Furniture and home furnishings
3322	443000	Retail Services - Electronics and appliances

3323	444000	Retail Services - Building material and garden supply
3324	445000	Retail Services - Food and beverage
3325	446000	Retail Services - Health and personal care
3326	447000	Retail Services - Gasoline stations
3327	448000	Retail Services - Clothing and clothing accessories
3328	451000	Retail Services - Sporting goods, hobby, book and music
3329	452000	Retail Services - General merchandise
3330	453000	Retail Services - Miscellaneous
3331	454000	Retail Services - Nonstore, direct and electronic sales
3332	481000	Air transportation services
3333	482000	Rail transportation services
3334	483000	Water transportation services
3335	484000	Truck transportation services
3336	485000	Transit and ground passenger transportation services
3337	486000	Pipeline transportation services
3338	48A000	Scenic and sightseeing transportation services and support activities for transportation
3339	492000	Couriers and messengers services
3340	493000	Warehousing and storage services
3341	511110	Newspapers
3342	511120	Periodicals
3343	511130	Books
3344	5111A0	Directories and mailing lists
3345	511200	Software
3346	512100	Motion pictures and videos
3347	512200	Sound recordings
3348	515100	Radio and television entertainment
3349	515200	Cable and other subscription services
3350	516110	Internet publishing and broadcasting services
3351	517000	Telecommunications
3352	5181	Data processing- hosting- ISP- web search portals
3353	519100	Other information services
3354	52A000	Monetary authorities and depository credit intermediation services
3355	522A00	Nondepository credit intermediation and related services
3356	523000	Securities, commodity contracts, investments, and related services
3357	524100	Insurance
3358	524200	Insurance agencies, brokerages, and related services
3359	525000	Funds, trusts, and other financial services
3360	531000	Real estate buying and selling, leasing, managing, and related services
3361	S00800	Imputed rental services of owner-occupied dwellings
3362	532100	Automotive equipment rental and leasing services
3363	532A00	General and consumer goods rental services except video tapes and

		discs
3364	532230	Video tape and disc rental services
3365	532400	Commercial and industrial machinery and equipment rental and leasing services
3366	533000	Leasing of nonfinancial intangible assets
3367	541100	Legal services
3368	541200	Accounting, tax preparation, bookkeeping, and payroll services
3369	541300	Architectural, engineering, and related services
3370	541400	Specialized design services
3371	541511	Custom computer programming services
3372	541512	Computer systems design services
3373	54151A	Other computer related services, including facilities management
3374	541610	Management, scientific, and technical consulting services
3375	5416A0	Environmental and other technical consulting services
3376	541700	Scientific research and development services
3377	541800	Advertising and related services
3378	541920	Photographic services
3379	541940	Veterinary services
3380	5419A0	All other miscellaneous professional, scientific, and technical services
3381	550000	Management of companies and enterprises
3382	561300	Employment services
3383	561500	Travel arrangement and reservation services
3384	561100	Office administrative services
3385	561200	Facilities support services
3386	561400	Business support services
3387	561600	Investigation and security services
3388	561700	Services to buildings and dwellings
3389	561900	Other support services
3390	562000	Waste management and remediation services
3391	611100	Elementary and secondary education from private schools
3392	611A00	Education from private junior colleges, colleges, universities, and professional schools
3393	611B00	Other private educational services
3394	621A00	Offices of physicians, dentists, and other health practitioners
3395	621600	Home health care services
3396	621B00	Medical and diagnostic labs and outpatient and other ambulatory care services
3397	622000	Private hospital services
3398	623000	Nursing and residential care services
3399	624400	Child day care services
3400	624A00	Individual and family services
3401	624200	Community food, housing, and other relief services, including rehabilitation services

3402	711100	Performing arts
3403	711200	Spectator sports
3404	711A00	Promotional services for performing arts and sports and public figures
3405	711500	Independent artists, writers, and performers
3406	712000	Museum, heritage, zoo, and recreational services
3407	713940	Fitness and recreational sports center services
3408	713950	Bowling activities
3409	713A00	Amusement parks, arcades, and gambling recreation
3410	713B00	Other amusements and recreation
3411	7211A0	Hotels and motel services, including casino hotels
3412	721A00	Other accommodation services
3413	722000	Restaurant, bar, and drinking place services
3414	8111A0	Automotive repair and maintenance services, except car washes
3415	811192	Car wash services
3416	811200	Electronic and precision equipment repairs and maintenance
3417	811300	Commercial and industrial machinery and equipment repairs and maintenance
3418	811400	Personal and household goods repairs and maintenance
3419	812100	Personal care services
3420	812200	Death care services
3421	812300	Dry-cleaning and laundry services
3422	812900	Other personal services
3423	813100	Services from religious organizations
3424	813A00	Grantmaking, giving, and social advocacy services
3425	813B00	Civic, social, and professional services
3426	814000	Cooking, housecleaning, gardening, and other services to private households
3427	491000	US Postal delivery services
3428	S-Fed Util	* Not a unique commodity (electricity from fed govt utilities)
3429	S00102	Products & services of Fed Govt enterprises (except electric utilities)
3430	S00201	* Not a unique commodity (passenger transit by state & local govt)
3431	S-State Util	* Not a unique commodity (electricity from state & local govt utilities)
3432	S00203	Products & services of State & Local Govt enterprises (except electric utilities)
3433	S00402	Used and secondhand goods
3434	S00401	Scrap
3435	S00900	Rest of the world adjustment
3436	S00300	Noncomparable foreign imports
3437	S00700	* Employment and payroll only (state & local govt, non-education)
3438	S00700	* Employment and payroll only (state & local govt, education)
3439	S00600	* Employment and payroll only (federal govt, non-military)
3440	S00500	* Employment and payroll only (federal govt, military)

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